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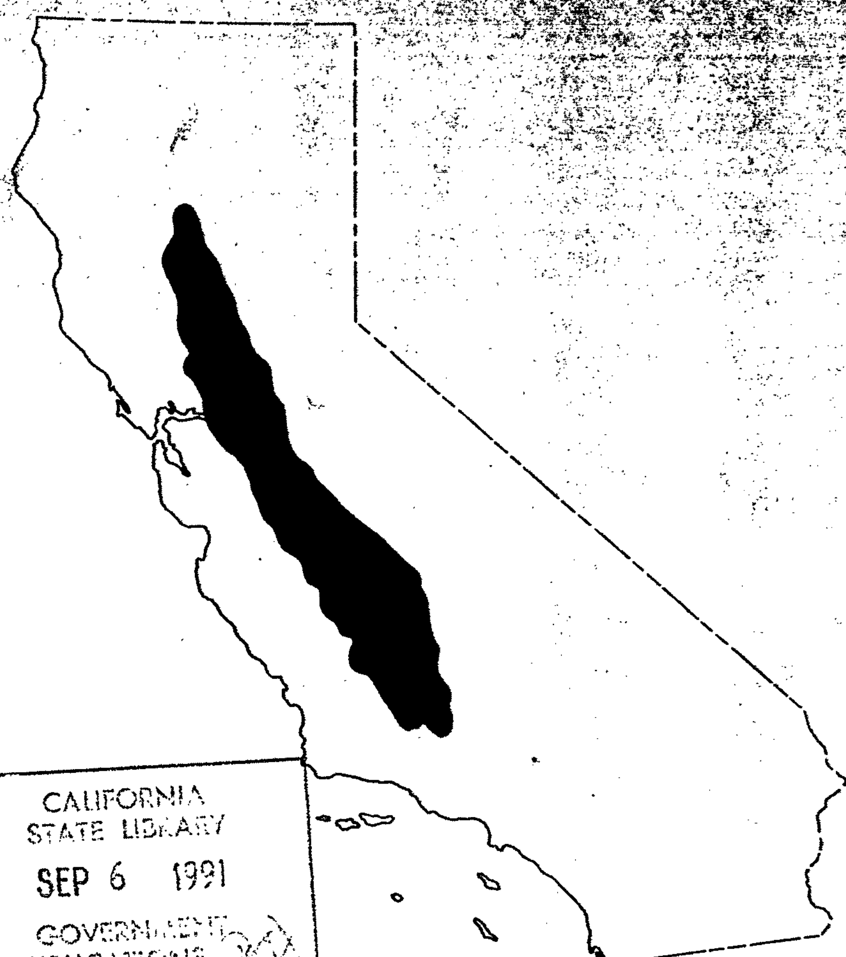
GROUND WATER IN THE CENTRAL VALLEY, CALIFORNIA— A SUMMARY REPORT

REGIONAL AQUIFER-SYSTEM ANALYSIS



U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1401-A

Ground Water in the Central Valley, California— A Summary Report

By GILBERT L. BERTOLDI, RICHARD H. JOHNSTON, *and* K.D. EVENSON

REGIONAL AQUIFER-SYSTEM ANALYSIS—CENTRAL VALLEY, CALIFORNIA

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-ft (acre-foot)	0.001233	cubic hectometer
acre-ft/yr (acre-foot per year)	0.001233	cubic hectometer per year
ft (foot)	0.3048	meter
ft/d (foot per day)	0.3048	meter per day
gal/min (gallons per minute)	0.06308	liter per second
(gal/min)/ft (gallons per minute per foot)	0.2070	cubic meter per second per meter
in. (inch)	25.4	millimeter
in./yr (inch per year)	25.4	millimeters per year
mi (mile)	1.609	kilometer
mi^2 (square mile)	2.590	square kilometer

In this report, "sea level" refers to the National Geodetic Vertical Datum (NGVD) of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called the Sea Level Datum of 1929.

GROUND WATER IN THE CENTRAL VALLEY, CALIFORNIA—A SUMMARY REPORT

By GILBERT L. BERTOLDI, RICHARD H. JOHNSTON, and K.D. EVENSON

ABSTRACT

The agricultural productivity of the Central Valley depends on irrigation. Half of the 22 million acre-feet of irrigation water applied annually is ground water. The valley is a long, narrow structural trough filled with about 32,000 feet of sediment in the south and as much as 50,000 feet in the north. Nearly all the fresh ground water is contained in the continental rocks and deposits younger than Eocene age. Streamflow, an important factor in recharging the aquifer system, is influenced by precipitation in the mountains surrounding the valley. The majority of recharge from infiltration of streamflow occurs on the east side of the valley.

Ground-water pumpage, which greatly exceeds the natural recharge rate, has dramatically altered the ground-water flow in the Central Valley. During the 1960's and 1970's, the recharge rate was more than five times that of the predevelopment period and was largely derived from percolation of imported surface water or recirculated pumped ground water rather than precipitation and recharge from streams. Prior to development, most ground water was discharged as evapotranspiration; however, in recent years, most discharge has been well pumpage. Computer simulation of the Central Valley aquifer system suggests that the total flow through the system has increased from about 2 million acre-feet per year to nearly 12 million acre-feet per year. The vertical movement of ground water has been artificially enhanced by many of the 100,000 irrigation wells that contain long intervals of perforated casing. When unpumped, these wells permit vertical flow between permeable layers within the aquifer system.

The total fresh ground water presently (1986) in storage in the upper 1,000 feet of the aquifer system is about 800 million acre-feet. During the 1960's and 1970's, ground water in storage was depleted at an average rate of 800,000 acre-feet annually.

In the San Joaquin Valley from the 1940's to the late 1960's, substantial withdrawals of ground water were accompanied by hundreds of feet of head decline. This head decline caused inelastic compaction of fine-grained beds, resulting in land subsidence that is unequaled anywhere else in the world. More than one-half of the San Joaquin Valley (or about 5,200 square miles) underwent subsidence of more than 1 foot. In one location, subsidence exceeded 29 feet. Within the areas of heavy withdrawals, subsidence is greatest where the aquifer system contains thick sections of montmorillonite clay. Land subsidence created engineering and economic problems, including damage to canals and drainage systems, and loss of irrigation wells caused by casing failure.

More recently (since the drought of 1976–77), surface-water imports have increased, ground-water pumpage has decreased, and in places, ground-water levels have recovered. Land subsidence has virtually ceased; however, it could resume with increased pumpage, if water levels decline below previous lows.

Ground-water quality in the Central Valley is generally influenced by the water from streams that are a major source of recharge. In general, water on the east side of the valley and from east-side streams contains low concentrations of dissolved solids compared to water on the west side and from west-side streams. Concentrations of dissolved solids in ground water generally are lower in the northern part of the valley than in the southern part. There are, however, localized exceptions in many places through the valley. Local concentrations of boron, chloride, and nitrate in the ground water of the Central Valley are large enough to be a problem either to crops or humans.

Human activities have some influence on the concentration and location of water-quality problems in the valley. Significant increases in concentrations of dissolved solids and, specifically, dissolved nitrate indicate that ground-water quality is degrading as a result of increasing application of fertilizer in agricultural areas and the growth of urban population. Pesticides such as dibromochloropropane (DBCP) as well as selenium and other trace elements in agricultural drainage water cause ecological and health problems in the San Joaquin Valley.

INTRODUCTION

In 1978 the U.S. Geological Survey began a series of ground-water investigations, the Regional Aquifer-System Analysis Program (RASA), as described in the "Foreword." The aquifer system in the Central Valley of California is one of 28 major aquifer systems in the country. It was selected for study because of the valley's long history of ground-water development and the importance of the area's agricultural production to the national economy (Bertoldi, 1979). Information needed for effective management of this aquifer system in the future includes (1) hydrogeologic framework of the valley, (2) hydraulic characteristics of the porous media (alluvium) through which ground water flows, (3) understanding of the ground-water-flow system including sources and rates of recharge and discharge, (4) chemical character of the ground water, (5) processes that control ground-water chemistry, and (6) effects of past and current human activities on the aquifer system.

The 5-year Central Valley aquifer study included the collection, analysis, and evaluation of data and prepara-

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tion of preliminary reports on water quality by Fogelman (1982a, 1982b, 1983); water use by Williamson (1981) and Diamond and Williamson (1983); hydrogeology by Page (1981, 1983), French, Page, and Bertoldi (1982, 1983), Page and Bertoldi (1983), French, Page, Bertoldi, and Fogelman (1983), and Berkstresser and others (1985); and ground-water hydraulics, regional flow, and aquifer mechanics by Williamson and Prudic (1986) and Prudic and Williamson (1986). In addition, Nady and Larragueta (1983a, 1983b) and Mullen and Nady (1985) described streamflow and irrigation development.

PURPOSE AND SCOPE

The purpose of Professional Paper 1401 is to describe major aspects of the geology, hydrology, and geochemistry of the Central Valley aquifer system. These descriptions are derived largely from the study results and preliminary reports of the 5-year study; however, they also utilize the extensive hydrologic literature on the California Central Valley (see references cited in chapters A–D).

Professional Paper 1401 consists of the following chapters:

Chapter A (this report) summarizes the important aspects of the geologic framework, regional ground-water flow, effects of development, and ground-water quality in the Central Valley.

Chapter B (Hull, 1984) describes the geochemistry of ground water in the Sacramento Valley.

Chapter C (Page, 1986) describes the geologic framework of the Central Valley, with emphasis on textural changes in the alluvial deposits that constitute the aquifer system.

Chapter D (Williamson and others, 1989) discusses ground-water hydraulics, with emphasis on an analysis of regional ground-water flow prior to and after extensive ground-water withdrawals. This regional analysis is based on computer simulation and presents a new, somewhat different concept of the aquifer system.

BASIN ENVIRONMENT

The Central Valley of California, viewed from the air or on a shaded relief map (fig. 1*A*), stands out as a notable topographic basin. It is about 400 mi long and averages about 50 mi in width. Surrounded on all sides by mountain ranges, the valley has only one natural outlet through which surface water drains. That outlet, the Carquinez Strait, cuts through the central Coast Ranges (fig. 1*A*) on the west boundary of the valley. In this study, the boundary of the Central Valley represents the areal extent of the valley's aquifer system rather than a physiographic boundary. The aquifer system's boundary is defined as coincident with the topographically highest occurrence of alluvial fan or alluvial plain deposits (alluvial boundary) of Pleistocene or Holocene age. In the northern part of the valley, discordant with the uniform flatness of the landscape, is the only notable topographic feature, Sutter Buttes (figs. 1*A* and 2). There, north and south Buttes, remnants of an ancient volcanic plug, rise to altitudes of 1,860 and 2,130 ft above sea level, respectively.

The Central Valley is composed of parts of four hydrographic subregions or drainage basins named for the major natural surface-water feature in each subregion (fig. 1*A*). Sacramento Valley, the northernmost third of the Central Valley, has an area of about 4,400 mi^2 and is drained by its namesake, the Sacramento River. Of the four hydrographic subregions, the Sacramento Valley is the least intensively developed. San Joaquin Valley, the southern two-thirds of the Central Valley, is made up of parts of two subregions: the San Joaquin Basin and, at the southern end, a basin of interior drainage called the Tulare Basin after a Pleistocene lake that occupied most of the area. The fourth hydrographic subregion is the Delta, a low-lying area that drains directly to the Sacramento-San Joaquin Delta rather than to either river (fig. 1*A*). The lower part of the Delta subregion consists of wetlands interspersed with hundreds of miles of channels and numerous islands.

Climate in the Central Valley is the Mediterranean type (Blair and Fite, 1957, p. 323). Average annual precipitation ranges from 13 to 26 in. in the Sacramento Valley and from 5 to 16 in. in the San Joaquin Valley. About 85 percent of the annual precipitation occurs from November to April. Summers are hot; winters are mild, allowing a long growing season. In contrast to the low precipitation in the valley, mean annual precipitation in the adjacent Sierra Nevada increases with altitude and ranges from 40 to more than 90 in. (Rantz, 1969). Much of the precipitation in the mountains is snow, especially in the higher southern Sierra Nevada. Variations in the volume of snowpack and delays in its melting produce differences in the timing of runoff in the two valleys. Peak runoff into the Sacramento Valley generally lags peak precipitation in the surrounding mountains by 1 to 2 months whereas peak runoff in the San Joaquin Valley generally lags peak precipitation by 5 to 6 months (fig. 3).

Streamflow, a very important factor in the water supply of the Central Valley, is almost entirely dependent on precipitation in the Sierra Nevada and part of the Klamath Mountains in the north (fig. 1*A*). No perennial streams of any significant size enter the valley from the west, except for Stony Creek, Cache Creek, and Putah Creek at the northwest end of the valley (fig. 1*B*). Mean annual streamflow entering the Central Valley around its perimeter is 31.7 million acre-ft.

Agriculture is the major commercial activity in the valley, providing jobs for about 30 percent of the population and cash receipts to farmers of about $13 billion in 1983. The Central Valley contains 5 of the top 10 agricultural counties (in value of crops sold) in the United States, including Fresno (number 1), Kern (number 2), and Kings (number 3). To support this level of agricultural activity in an area that is deficient in precipitation requires a substantial amount of irrigation water. During the 1960's and 1970's, an average of 22 million acre-ft of

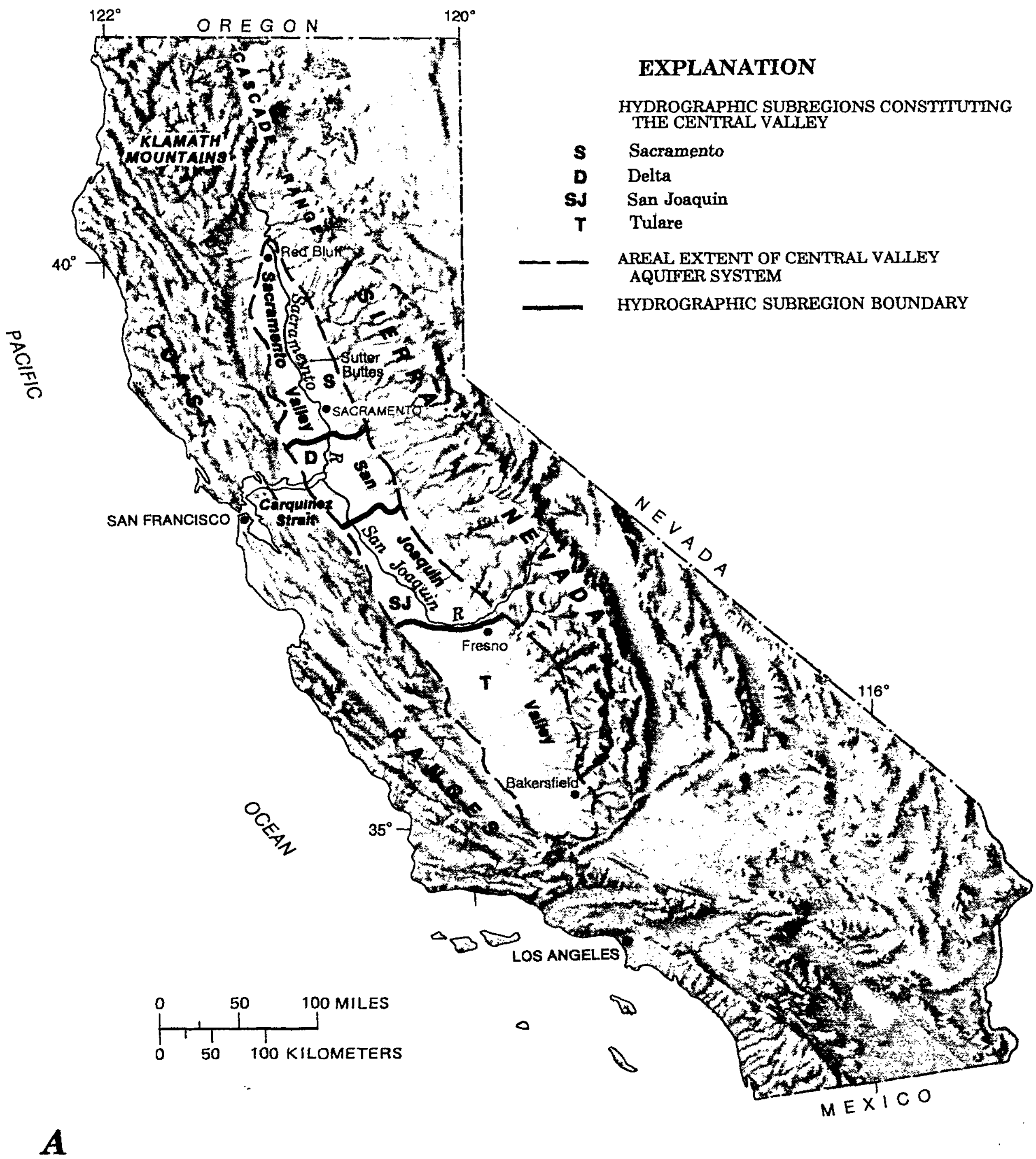

FIGURE 1.—Location of study area. *A*, Shaded relief map of California showing Central Valley drainage basins. *B*, Counties and cities of the Central Valley.

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irrigation water was required annually—about one-half from ground water and one-half from surface water. During drought years, the amount supplied by ground water increases; during wet years, the amount supplie by surface water increases. During the early to midd 1980's, the overall usage of irrigation water increase

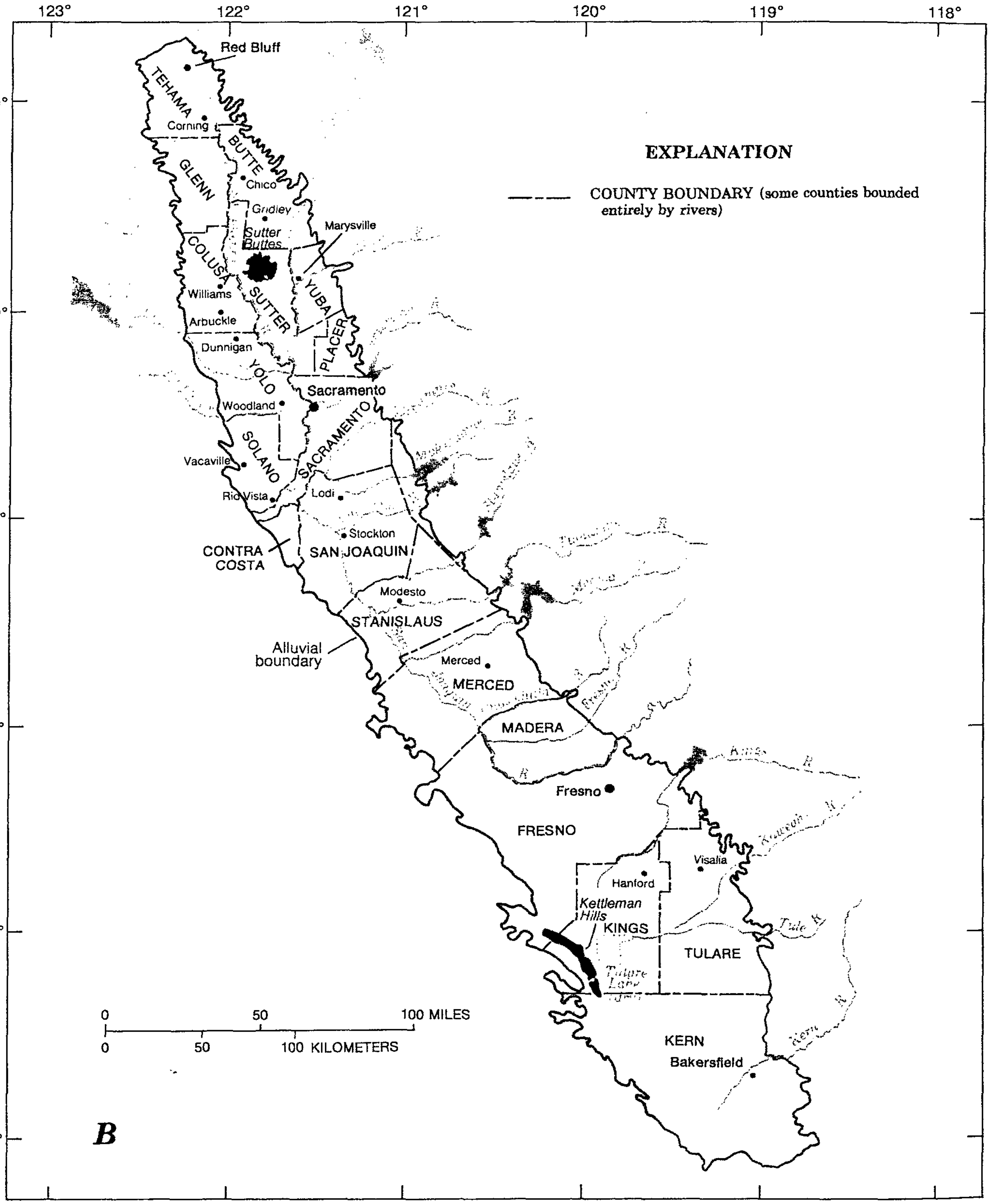

FIGURE 1.—Continued

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slightly and a higher proportion came from surface-water sources.

If precipitation and runoff were distributed uniformly in space and time, then average values could be relied upon by water users and managers. However, both precipitation and runoff in the valley vary widely during each year and from year to year (figs. 3, 4). The cumulative departure graphs (fig. 4) show wetter than normal periods (cumulative departure increases) and drier than normal periods (cumulative departure decreases) since the middle 1800's. Because annual precipitation at Fresno and Bakersfield is much less than at Red Bluff and Sacramento, the magnitude of departure is also much less.

A fairly stable measure of the variability of runoff in the Central Valley has been the sum of the annual flow of the 15 largest streams because one end of the Central Valley may have less-than-normal precipitation while the other end may have above-normal precipitation. Only twice between 1961 and 1977 was the total annual flow of the 15 largest streams within 10 percent of the mean annual flow of these streams, and only in 7 years of the 44-year-period record was the total annual flow within 10 percent of the mean annual flow. These records indicate

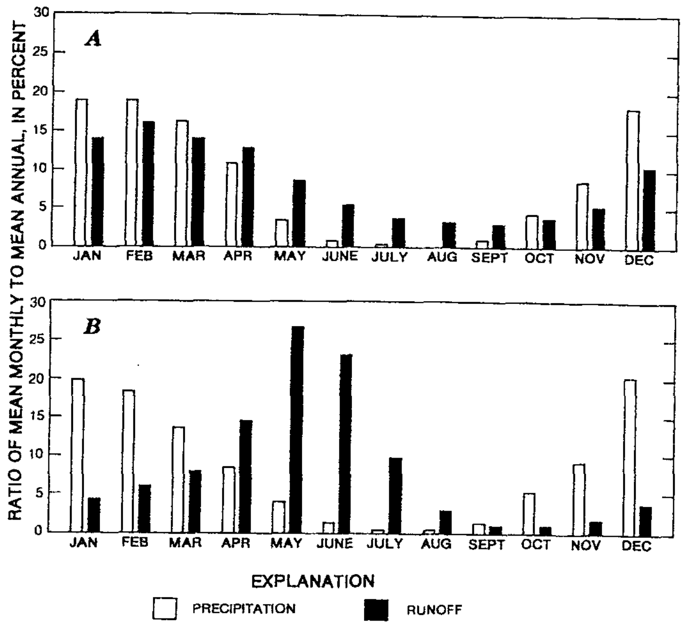

FIGURE 3.—Precipitation in the Sierra Nevada and runoff in the Central Valley (modified from Williamson and others, 1989). *A*, Sacramento Valley. *B*, San Joaquin Valley.

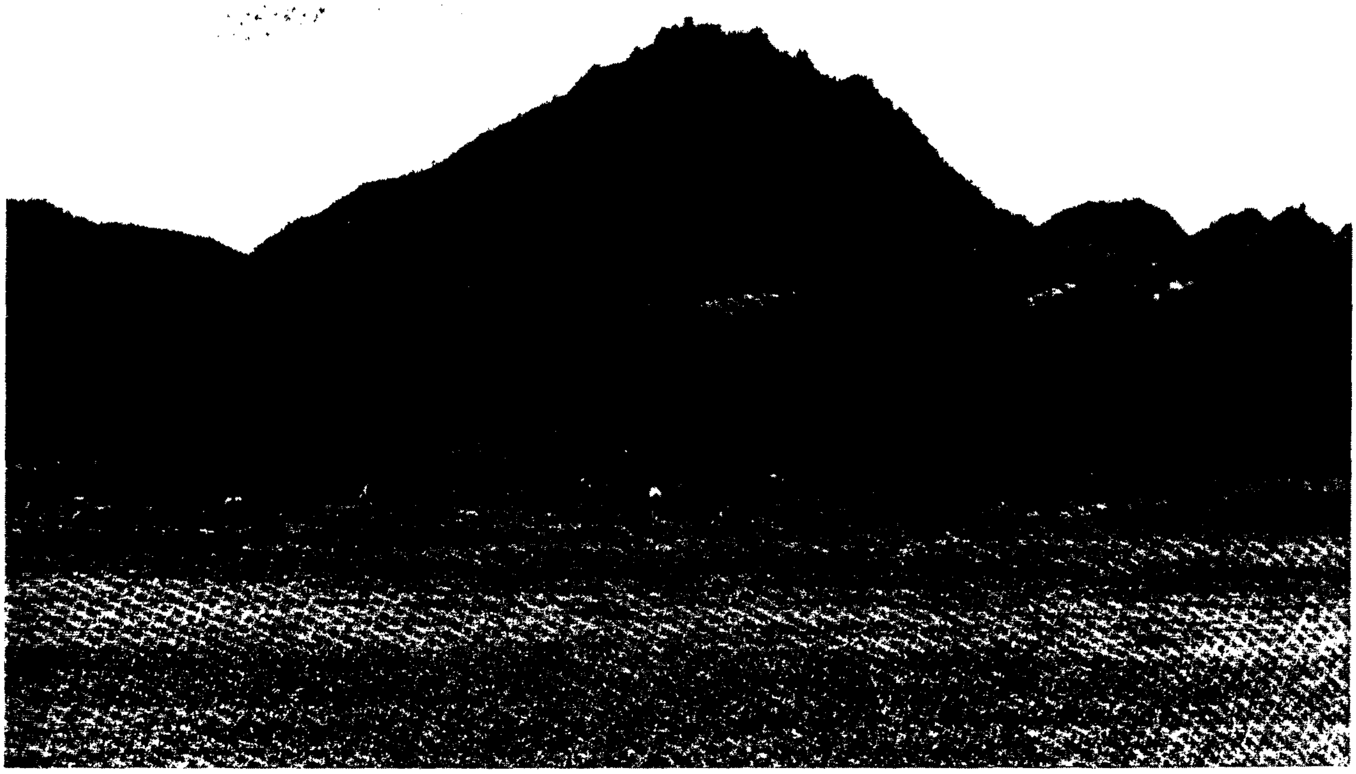

FIGURE 2.—Sutter Buttes. View northeastward from southwest edge of buttes.

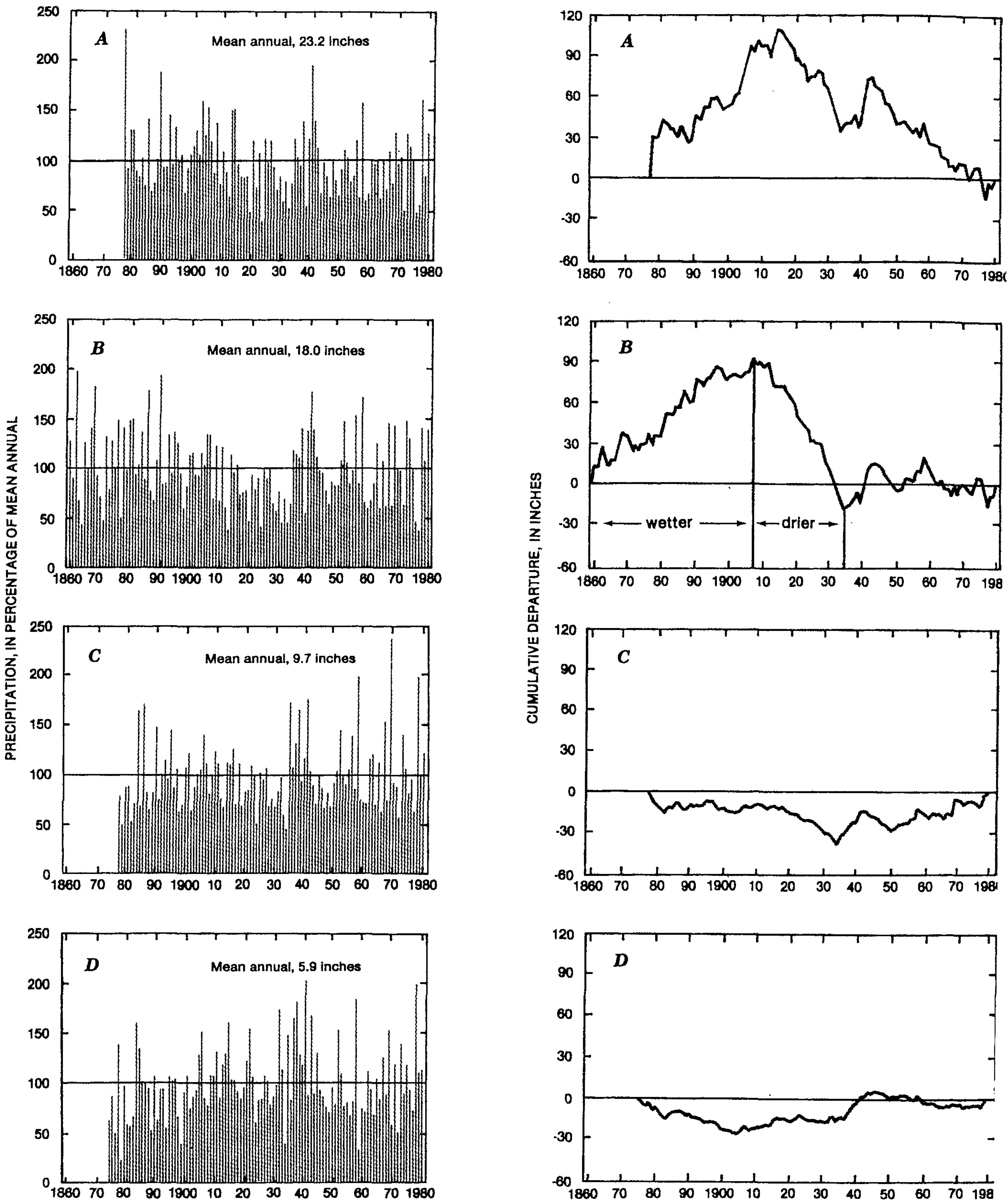

FIGURE 4.—Mean annual precipitation and cumulative departure of precipitation from mean value, 1860 to 1980, at four Central Valley stations (from Williamson and others, 1989). *A*, Red Bluff. *B*, Sacramento. *C*, Fresno. *D*, Bakersfield.

that runoff in the valley is highly variable. Because of such high variability of both precipitation and runoff, early settlers soon learned that ground water was a more dependable source than surface water.

PREVIOUS INVESTIGATIONS

Because of the long history of ground-water development and its severe impacts, many hydrologic investigations have been done in the Central Valley by the California Department of Water Resources, the U.S. Geological Survey, and various local agencies. The earliest systematic study of California's water resources was by Hall (1886, 1889). Two important early studies were a summary of ground-water resources in the San Joaquin Valley by Mendenhall and others (1916) and a description of the geology and ground-water resources in the Sacramento Valley by Bryan (1923). These two studies were particularly useful in the investigations of the regional flow system described in chapter D of this series (Williamson and others, 1989) because they documented hydrologic conditions prior to large-scale irrigation development.

In the early 1950's, the State of California and the U.S. Geological Survey cooperated in a series of ground-water reconnaissance studies that revealed nearly continuous annual declines of ground-water levels for large areas of the San Joaquin Valley and for some interstream areas of the Sacramento Valley. Two reports prepared during the 1950's provided summary descriptions of the ground-water hydrology of the San Joaquin Valley (Davis and others, 1959) and the Sacramento Valley (Olmsted and Davis, 1961).

Comprehensive investigations of land subsidence in the San Joaquin Valley have been carried out since the 1950's by the U.S. Geological Survey under the direction of Joseph F. Poland. These landmark studies clearly show the relation between ground-water-level decline, compaction of fine-grained sediments, and land subsidence. Land subsidence in the Central Valley was described in several reports by Bull (1972), Lofgren (1975), Bull and Miller (1975), Bull (1975), Bull and Poland (1975), Poland and others (1975), and Ireland and others (1984). The mechanics of compacting sediments were described by Meade (1964, 1967, 1968), Riley (1970), Miller and others (1971), and Poland and Ireland (1988).

A bibliography of nearly 600 reports that describe ground water in the Central Valley was compiled by Bertoldi (1979).

WELL-NUMBERING SYSTEM

Wells are identified according to their location in the rectangular system used for the subdivision of public lands. The identification consists of the township number, north or south of a base line; the range number, east or west of a meridian; and the section number. A section is divided into sixteen 40-acre tracts lettered consecutively (excluding I and O), beginning with A in the northeast corner of the section and progressing to R in the southeast corner (fig. 5). Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian relative to which the townships and ranges are numbered. For the Central Valley, this is the Mount Diablo base line and meridian (M).

HYDROGEOLOGY

The Central Valley is a long, narrow, northwest-trending, asymmetric structural trough that has been filled with about 32,000 ft of sediment in the southern part and as much as 50,000 ft in the northern part (Page,

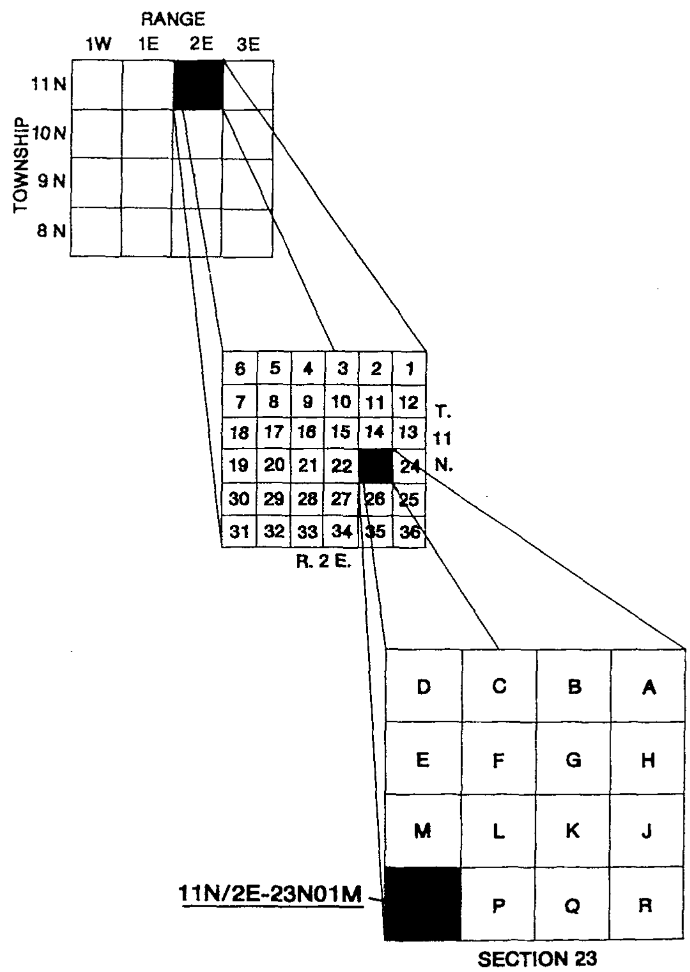

FIGURE 5.—Well-numbering system.

1986). Sedimentary deposits include both marine and continental deposits and range in age from Jurassic to Holocene. The valley is bordered on the east by the Sierra Nevada and on the west by the Coast Ranges (fig. 6). The Sierra Nevada is the source of most of the sediment that underlies the valley.

GEOLOGIC SETTING

Although there are differing viewpoints among geologists as to the details of the origin of structural features we can view today in the Central Valley, there is general agreement on the larger aspects of the emergence of California as a landmass and the subsequent formation of the valley (King, 1977, p. 177). The formation of the Sierra Nevada and the Coast Ranges is important to understanding the deposition of aquifer material in the Central Valley as well as to understanding the distribution and movement of ground water.

To the east of the Central Valley is the Sierra Nevada. It is the largest single mountain range in the conterminous United States and is about 350 mi long and 55 to 80 mi wide—about as long and wide as the Central Valley. The Sierra Nevada is composed primarily of granite and related plutonic rocks but includes metasedimentary and metavolcanic rocks that range in age from Late Jurassic to Ordovician or perhaps older. The Sierra Nevada batholith was emplaced after the Late Jurassic but prior to the Late Cretaceous (Shelton, 1966, p. 385).

The Sierra Nevada, like the Central Valley, is asymmetric; the east side is considerably steeper than the west side (fig. 6), suggesting that the block was tilted upward toward the east. At the base of the east slope is evidence of recent faulting at several locales, while steep canyons have been cut into the gently sloping west side. Based on the steep canyons, Shelton (1966, p. 388) deduced that the huge granitic batholith was at a low elevation long enough to acquire a fairly flat erosional surface before it was tilted in successive stages. Wells drilled in the San Joaquin and Sacramento Valleys penetrated granitic rocks at increasing depths toward the west, indicating that the granite exposed in the Sierra Nevada is only a small part of the whole mass.

Uplift of the granitic rocks resulted in increased precipitation in the Sierra Nevada, particularly near its crest, which in places exceeds 14,000 ft altitude. Warm, moist airmasses from the Pacific Ocean are forced aloft by the mountain range, causing the airmasses to cool and the moisture to condense, resulting in heavy precipitation that exceeds 80 in./yr in places (Rantz, 1969). Because the crest of the range is near the east side, much of the runoff is westward to the Central Valley and is a major source of water to the valley. The streams that debouch from the Sierra Nevada also have supplied a major part of the recent and older Cenozoic sediments that have been deposited in the valley.

Bailey and others (1970) described the significance and processes of the overland thrusting of the Mesozoic marine sediments to the formation of the Coast Ranges and to the deformation of the Great Valley sequence. Two important hydrologic points can be made from Bailey's geologic discussion. First, the emergence of the Coast Range thrust and subsequent development of the Coast Ranges established an orographic barrier for moisture-laden onshore oceanic winds; as a result, the Central Valley effectively was put into a rain shadow since the formation of its west boundary—an important factor in considering the source and distribution of ground-water recharge to the valley. A second factor that needs to be emphasized is the extensive deformation of the marine beds of the Great Valley sequence on the west side of the valley. In addition to establishing the asymmetric nature of the valley trough, these highly contorted beds may form a fault zone under the west side of the valley (Oakeshott, 1971, p. 289). The fault zone and the beds are barriers to ground-water flow. Variations in the chemical quality of ground water and in hydraulic heads are observed in closely spaced wells of similar construction drilled near the east boundary of the Coast Ranges (Hotchkiss and Balding, 1971).

Although the ancestral Sacramento and San Joaquin Valleys were created by the emergence of many areas of the Coast Ranges by middle Cretaceous time, parts of the Central Valley remained inundated by the Pacific Ocean until late Pliocene time (about 2 to 3 million years before present). These inundated areas were continuously changing in size and shape as the Coast Ranges emerged. As a result, both marine and continental sediments were deposited. Marine deposition was dominant in the Central Valley from the Paleocene to the beginning of the Oligocene (fig. 7). During the early Oligocene, marine deposition was restricted to the southern part of the San Joaquin Valley; during the Miocene, marine deposits were laid down along the west flank of the San Joaquin Valley and throughout most of the southern San Joaquin Valley (fig. 7). The seas had retreated by the Pleistocene, and only continental sediments were deposited during the Pleistocene and Holocene.

Marine deposits of Tertiary age, therefore, underlie large parts of the Central Valley; they crop out around Sutter Buttes, along the southwest flank of the Sacramento Valley, and along the west, southwest, south, and southeast flanks of the San Joaquin Valley.

Because of many changes in the depositional environment, the marine deposits differ greatly in sediment type, sorting, and thickness, and have been given numerous names by petroleum geologists (Park and Weddle, 1959, pl. 3; Sacramento Petroleum Association, 1962, figs. 6, 7, 10, 20, and 27, and table 2). In places the marine deposits provided the source material for the overlying continental deposits that form the freshwater aquifers of the valley. Generally, the marine deposits contain saline water, some of which has migrated into adjacent and overlying freshwater aquifers.

In a few places in the San Joaquin Valley, the marine rocks and deposits have been flushed of saline water and contain freshwater, which they yield to wells. In the Sacramento Valley, no marine deposits were reported as yielding freshwater to wells, although Olmsted and Davis (1961, p. 134) reported that marine rocks were flushed of connate water locally. The marine rocks, then, provide very little freshwater in the Central Valley.

Continental deposits of post-Eocene age overlie the marine deposits and contain most of the freshwater aquifers in the Central Valley. An important contribution to the quantification of storage capacity in the aquifer system was made when Page (1983) successfully mapped texture change in the continental deposits overlying predominantly marine rocks and deposits in about 1,000 mi^2 of the San Joaquin Valley.

In this report and in chapter D (Williamson and others, 1989), the base of the aquifer system is taken as coincident with the base of the post-Eocene continental deposits. This is not strictly true in the southeastern San Joaquin Valley where sandy marine beds underlying the continental deposits contain freshwater and are hydrologically part of the aquifer system. The thickness of the aquifer system, based largely on a thickness map of post-Eocene continental deposits prepared by R.W. Page (U.S. Geological Survey, written commun., 1981; Page, 1974), is shown in figure 8. The thickness of the aquifer system averages about 2,400 ft and increases from north to south, with a maximum thickness of more than 9,000 ft near Bakersfield. However, the contact between continental and the underlying marine deposits is not always certain because the two types of deposits interfinger in some places, particularly near the south end of the valley. DeLaveaga (1952, p. 102) suggested that the continental

FIGURE 6.—Generalized oblique view (northward) of part of Central Valley structural trough. Coast Ranges lie to the east; Sierra Nevada to the west. (From "Geology Illustrated" by John S. Shelton. Copyright 1966, W.H. Freeman and Company. Used with permission.)

deposits may be as much as 15,000 ft thick, but 9,000 ft is shown as the maximum aquifer system thickness (fig. 8). The omission of all continental deposits beneath the 9,000-foot level does not affect the analysis of groundwater flow (described later) because (1) the total probable volume affected is less than 1 percent of the total volume of the aquifer system and (2) the deeper part of the continental deposits is so far below practical pumping

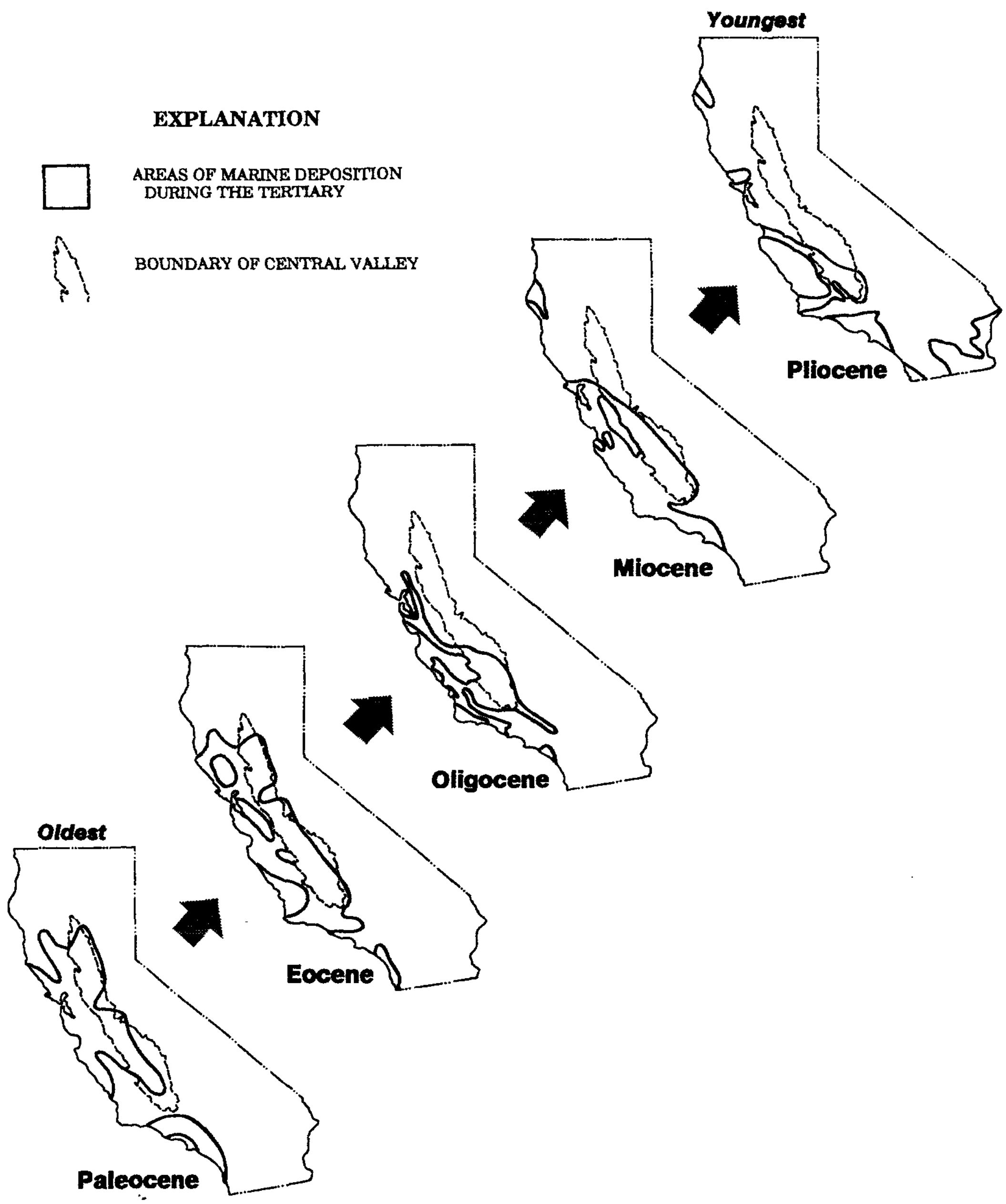

FIGURE 7.—Approximate areas of marine deposition during the Tertiary.

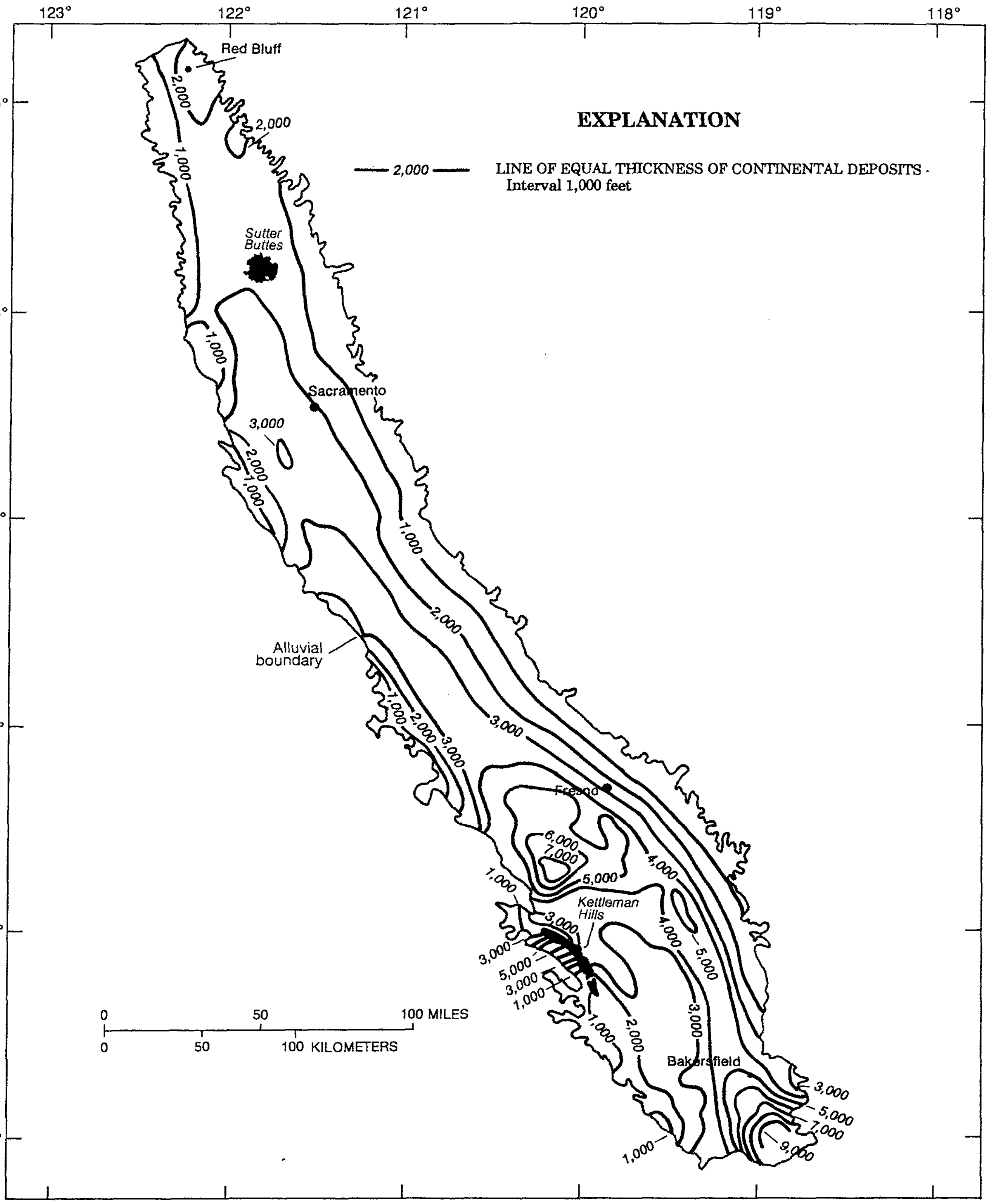

FIGURE 8.—Thickness of Central Valley aquifer system (largely post-Eocene continental deposits). From Page (1974) and R.W. Page (U.S. Geological Survey, written commun., 1981).

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limits that an error in estimating their thickness has no effect on the flow-system analysis.

WATER-BEARING CHARACTERISTICS OF THE AQUIFER SYSTEM (POST-EOCENE CONTINENTAL DEPOSITS)

The post-Eocene continental deposits that constitute the Central Valley aquifer system contain mostly fluvial deposits and interbedded lacustrine deposits but include some volcanic material. The continental deposits consist predominantly of lenses of gravel, sand, silt, and clay. The numerous lenses of fine-grained (silt, sandy silt, sandy clay, and clay) sediments are distributed throughout the valley and in most places constitute over 50 percent of the total thickness penetrated by wells, as determined from electric logs (Page, 1986).

Most of these fine-grained lenses are not areally extensive; however, several major ones were mapped, principally near the axis of the San Joaquin Valley. The most notable is the Corcoran Clay Member (Pleistocene) of the Tulare Formation (Pliocene and Pleistocene), which is part of the modified E-clay of Page (1986) and underlies most of the west side of the San Joaquin Valley. This diatomaceous clay unit underlies an area of approximately 5,000 mi^2 (Page, 1986) and ranges in thickness from near zero to at least 160 ft beneath the present bed of Tulare Lake (Davis and others, 1959; Page, 1986). The northern extent of the Corcoran Clay Member is not known because of the lack of well data north of Stockton, particularly in the Delta area. A diatomaceous clay similar in composition to that of the Corcoran Clay Member was present in a test hole drilled northwest of Sacramento, and drillers have filed reports showing a diatomaceous clay in several deeper wells north of Stockton (Page and Bertoldi, 1983). Laboratory tests of the clay indicate that it is highly susceptible to compaction, like the Corcoran Clay Member; however, the clay was not present in six other test holes northwest of Sacramento, so the full extent of it is not known.

The Corcoran Clay Member is important to the hydraulics of the aquifer system in that prior to development it acted as an effective confining unit. However, the drilling of large-diameter wells through the Corcoran and the practice of perforating wells both above and below it have made the present effectiveness of the Corcoran as a confining unit questionable.

In the basis of drillers' logs, electric logs from gas wells and the water wells, plus-information from seven U.S. Geological Survey test holes drilled as part of this study, Page (1986) concluded that no extensive fine-grained lenses underlie the Sacramento Valley. However, there are two areas of mostly fine-grained sediments interbedded with coarse-grained sediments along the northeast flank of the Sacramento Valley adjacent to and south of Chico (Page, 1986, fig. 8), at depths from 600 to 900 ft, and along the southwest flank of the Sacramento Valley north of Cache Creek in T. 3 N., at depths from about 600 to 2,700 ft (Page, 1986, figs. 8–14).

Relating aquifers within the post-Eocene continental deposits to specific formations in the subsurface is difficult. In the valley, investigators use mainly physiography, weathering characteristics, and soils to map upper Cenozoic formations; however, in the subsurface, especially under saturated conditions, equivalents of surface units cannot be mapped with any certainty because differences in lithology are not apparent. In the Central Valley, then, physical properties of the aquifer materials and the distribution of these properties are more important than the delineation of formation boundaries to understanding regional and local flow patterns and to quantifying water in storage. The general relations in the Sacramento and San Joaquin Valleys among geologic units, hydrologic units, and layers used in the computer simulation of ground-water flow are shown in figure 9.

STORAGE COEFFICIENT

Storage coefficient is the amount of water that can be released from or added to the ground-water reservoir. It is usually defined as the volume of water an aquifer system releases from or takes into storage per unit surface area of aquifer per unit change in head (Lohman and others, 1972, p. 8). In the zone of water-table fluctuations, the storage coefficient is virtually equal to the amount of water released from storage by gravity drainage, referred to as specific yield. Below the zone of water-table fluctuations, the storage coefficient is the amount of water released by compression of the sediments and expansion of the water. This amount is usually much less than the amount released by gravity drainage.

Laboratory values of specific yield and porosity are shown in table 1. For the purposes of uniformity, only reported values obtained by the "sample saturation and drainage" method described by Johnson (1967, p. D5) were used in table 1. In general, sand yields more water from gravity drainage than fine-grained deposits like silt and clay, even though the porosities are nearly the same. The fine-grained deposits usually have much smaller specific-yield values because the tiny pores do not drain readily.

Williamson and others (1989, table 7) used specific-yield values for aquifer materials similar to those shown in table 1 and then estimated an aggregated specific yield for the first few hundred feet of saturated sediment on the basis of lithologic descriptions from about 17,000 well logs. They estimated an average specific yield of 7 percent for the Sacramento Valley, 8 percent for the Delta area, and 10 percent for the San Joaquin Valley and Tulare Basin.

The Central Valley aquifer system contains numerous fine-grained (clay and silt) randomly distributed lenses that, in general, constitute over 50 percent of the total thickness of the system. Because of the large percentage of fine-grained sediments, Williamson and others (1989, table 7) concluded that the part of the aquifer system

	Generalized section of geologic units. Reported maximum thickness, in feet, is in parentheses (adapted from Page, 1986, table 1)	**Hydrologic unit used in many reports such as Bloyd (1978)**	**Layers in digital flow model (Williamson and others, 1989)**
Quaternary	**Flood basin deposits (160)** -- Primarily clay, silt, and some sand; include muck, peat, and other organic soils in Delta area. Restrict yield to wells and impede vertical movement of water. **River deposits (115)** -- Primarily gravel, sand, and silt; include minor amounts of clay. Among the more permeable deposits in valley.	Unconfined to locally confined aquifer	**Layer 4** Most wells tap this layer; unconfined storage
Tertiary and Quaternary	**Continental rocks and deposits (3,000 ±)** -- Heterogeneous mix of poorly sorted clay, silt, sand, and gravel; include some beds of claystone, siltstone, and sandstone. Younger deposits (Pliocene to Holocene) form major aquifer system in valley. Older deposits (Eocene to Pliocene) include breccia, conglomerate, and some volcanic rocks and deposits. Older deposits close to land surface on east side are generally small yield aquifers. **Volcanic rocks and deposits (1,000)** -- Younger (Pliocene and Pleistocene) rocks and deposits include tuff and tuff breccia associated with Sutter Buttes; locally important source of water. Older (Miocene and Pliocene) volcanic rocks and deposits include andesite, obsidian, pumice, tuff, volcanic breccia, gravel, sand, volcanic mud flows, and some basalt. The rocks and deposits are important aquifers in the northeast part of valley where close to land surface.		**Layer 3** Some wells tap this layer; elastic and inelastic confined storage
			Layer 2 No wells; elastic and inelastic confined storage
			Layer 1 No wells; elastic confined storage

A

	Generalized section of geologic units. Reported maximum thickness, in feet, is in parentheses (adapted from Page, 1986, table 2)	**Hydrologic unit used in many reports such as Poland and Lofgren (1984)**	**Layers in digital flow model (Williamson and others, 1989)**
Quaternary	**Flood basin deposits (100)** -- Primarily clay, silt, and some sand; include muck, peat, and other organic soils in Delta area. Restrict yield to wells and impede vertical movement of water. **River deposits (100±)** -- Primarily gravel, sand, and silt; include minor amounts of clay. Among the more permeable deposits in valley.	Upper water-bearing zone[1]; unconfined to semiconfined Principal confining unit (modified E clay) / Absent	**Layer 4** Many wells tap this layer; unconfined storage
Tertiary and Quaternary	**Lacustrine and marsh deposits (3,600+)** -- Primarily clay and silt; include some sand. Thickest beneath Tulare Lake bed. Include three widespread clay units -- A, C, and modified E clay. Modified E clay includes the Corcoran Clay Member of the Tulare Formation. Impede vertical movement of water.	Lower water-bearing zone[1]; semiconfined to confined. Extends to base of fresh-water which is variable	**Layer 3** Many wells tap this layer; elastic and inelastic confined storage
	Continental rocks and deposits (15,000) -- Heterogeneous mix of poorly sorted clay, silt, sand, and gravel; include some beds of mudstone, claystone, shale, siltstone, sandstone, and conglomerate. Form major aquifer system in valley.	Base of freshwater	**Layer 2** Some wells tap this layer; elastic and inelastic confined storage
Tertiary	**Marine rocks and deposits** -- Primarily sand, clay, silt, sandstone, shale, mudstone, and siltstone. Locally yield fresh water to wells, mainly on the southeast side of the valley but also on the west side near Kettleman Hills.	Below the depth of water wells. In many areas, post-Eocene deposits contain saline water	**Layer 1** No wells; elastic confined storage

[1] The upper and lower water-bearing zones are undifferentiated where the modified E clay (includes Corcoran Clay Member of the Tulare Formation) is absent.

B

FIGURE 9.—Geologic and hydrologic units and equivalent layers in digital flow model. *A*, Sacramento Valley. *B*, San Joaquin Valley.

TABLE 1.—*Laboratory values of selected hydraulic and physical properties of unconsolidated sediment in the Central Valley*

[ft/d, feet per day; <, less than; —, no data]

Sediment size	Number of samples used to determine specific yield and porosity	Specific yield[1] (percent)	Porosity[1] (percent)	Average hydraulic conductivity[2] (ft/d)	
				Vertical	Hori-zontal
Sand	126	19–35 / 27	31–65 / 40	11.5	14
Clayey sand	28	10–28 / 16	28–52 / 37	—	—
Sand-silt-clay	95	2–20 / 12	31–56 / 37	.02	.02
Clayey silt	107	<1–7 / 3.5	32–61 / 42	.0001	—
Silty sand	137	<1–15 / 7.5	25–41 / 34	.21	.16
Sandy silt	49	1–12 / 7.5	34–37 / 36	.02	.13
Silt	79	1–7 / 3	34–56 / 43	.0002	—
Silty clay	86	<1–8 / 4	35–52 / 43	.0001	.002
Clay	0	No pure clays analyzed		—	—

[1]Range of values above line; mean value below line. Specific yield and porosity values were compiled from Stearns and others (1930), Piper and others (1939), Johnson (1967), and Johnson and others (1968).

[2]Laboratory determinations of hydraulic conductivity values were obtained from the U.S. Bureau of Reclamation, Sacramento, California, and Johnson and others (1968).

below the upper few hundred feet should be considered confined in the sense that the vertical permeabilities of sediments are much lower than the horizontal permeabilities. In the confined aquifers, water released by compression of fine-grained lenses, rather than that released from dewatering of pore space, may be the major source of water release from storage (Jacob, 1940). Therefore, it is necessary to define and measure another storage parameter, specific storage (S_s). This parameter is the volume of water released from or taken into storage per unit volume of aquifer material per unit change in head (Lohman and others, 1972, p. 13). Below the zone of water-table fluctuation, only S_s and the thickness of the aquifer are used to calculate water in storage. However, when effective (grain-to-grain) stress is increased, some of the fine-grained lenses undergo reorientation and deformation. Therefore, S_s has two significant values. If water released from storage is due to the expansion of water and compressibility of the aquifer in response to a decrease in hydraulic head, the specific storage is elastic. Conversely, if a decrease in hydraulic head causes deformation and reorientation of sediments in fine-grained lenses, the specific storage is inelastic. The coefficients of elastic and inelastic specific storage derived from field tests and computer simulation are shown in table 2. Note that values of inelastic specific storage are much larger than those of elastic specific storage. For their simulation of regional ground-water flow, Williamson and others (1989) used the average specific-storage values in table 2.

HYDRAULIC CONDUCTIVITY

The term "hydraulic conductivity" (K) allows relative comparison of the transmission properties of different aquifers or parts thereof. The hydraulic conductivity of a saturated porous medium (aquifer material) is the volume of water that the material will transmit in a unit of time through a cross section of unit area, under a hydraulic gradient of unit change in head through a unit length of flow (Lohman and others, 1972, p. 6).

Average horizontal hydraulic conductivity (K_h) in the valley ranged from 14 ft/d for sand to 0.002 ft/d for silty clay (table 1) as determined from laboratory tests of core

TABLE 2.—*Specific-storage values (S_s) for aquifers in the Central Valley*

Source of data	Specific-storage coefficient (per foot) Fine grained	Coarse grained	Remarks
		Elastic	
Poland (1961, p. B53)	—	1.4×10^{-6}	Assumed 1,000 ft of aquifer thickness of which 700 ft is coarse and 300 ft is fine. Estimate is for coarse material only.
Riley and McClelland (1972, p. 77)	—	0.7 to 1×10^{-6}	Detailed leaky-aquifer analysis of pumping tests near Fresno, San Joaquin Valley.
Helm (1978, p. 193))	4.5×10^{-6}	—	Average of several model runs.
		Inelastic	
Poland (1961, p. B53)	2×10^{-4}	—	For 300 ft of clay with inelastic storage coefficient of 5×10^{-2}.
Helm (1978, p. 193)	3×10^{-4}	—	Average for seven sites; range, 1.4×10^{-4} to 6.7×10^{-4}.

samples. However, the average K_h of the entire Central Valley aquifer system is estimated to be 6 ft/d based on calibration of a regional ground-water flow model (Williamson and others, 1989). This value is somewhat less than the average value for sand but probably reflects the lateral discontinuity of sand beds and more accurately represents the conductivity that controls ground-water flow on a regional scale. The average hydraulic conductivity of the Sacramento Valley is about one-half the average for the San Joaquin Valley, probably because of more fine-grained volcanic-derived sediments in the Sacramento Valley (Williamson and others, 1989).

GROUND-WATER FLOW SYSTEM

REGIONAL FLOW

Regional ground-water flow in the Central Valley is strongly influenced by the numerous clay and silt lenses that are present in the aquifer system. Different viewpoints on the role of the fine-grained lenses have resulted in two concepts of the aquifer system, as follows:

1. Until recently, most investigators considered the Sacramento Valley as containing one unconfined aquifer (Bloyd, 1978) and the San Joaquin Valley as containing two aquifers separated by a regional confining unit. The San Joaquin sequence was described in descending order by Poland and Lofgren (1984) as a semiconfined aquifer (upper water-bearing zone), a regional confining unit (Corcoran Clay Member of the Tulare Formation), and a confined aquifer (lower water-bearing zone).
2. More recently, Williamson and others (1989) proposed the concept of a single heterogeneous aquifer system for the Central Valley. This concept is that "the entire thickness of continental deposits is one aquifer system that has varying vertical leakance and confinement depending upon the properties of fine-

grained sediments." Below the upper few hundred feet everywhere, they consider the aquifer to be virtually confined. These two concepts of the aquifer system in the Central Valley are shown in figure 10.

Lithologic studies described in chapter C (Page, 1986) show that the aquifer system contains many isolated lenses of sand, silt, and clay. The fine-grained lenses, although limited in lateral extent, constitute more than 50 percent of the system and have an aggregate thickness of as much as several thousand feet. In contrast, the Corcoran Clay Member, a confining unit, ranges in thickness from zero to 160 ft and has an average thickness of 55 ft (Williamson and others, 1989). Vertical head differences are present nearly everywhere in the Central Valley. Head differences, as much as 400 ft, were observed in wells of different depths in some areas on the west side of the San Joaquin Valley. These large head differences result from very heavy pumpage in the lower zone combined with the resistance to vertical flow provided by the fine-grained lenses in the aquifer system. Although some head difference in wells is observed across the Corcoran Clay Member, an even greater head difference occurs in wells that tap the intervals above and below the Corcoran. In addition, numerous wells that contain perforated sections both above and below the Corcoran Clay Member show little vertical head difference. Thus, the Corcoran is much less important than the combined effect of the many fine-grained lenses in controlling vertical flow. In summary, the concept of a single heterogeneous aquifer system is supported by the presence of numerous fine-grained lenses and the hydraulic response of the system to pumping.

The concept of a single, mostly confined, heterogeneous aquifer system was used as the basis for the computer simulation of regional ground-water flow described in

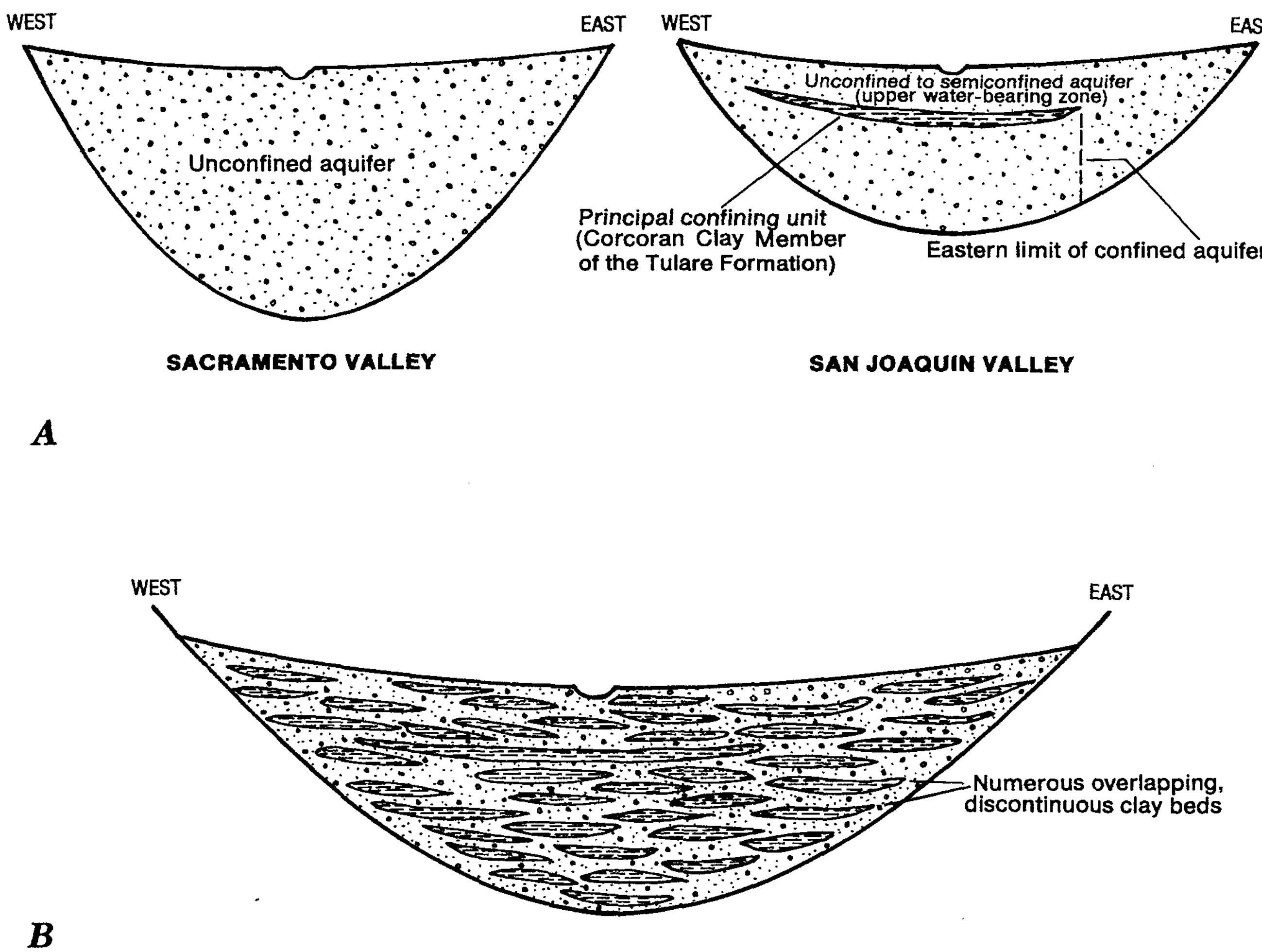

FIGURE 10.—Concepts of Central Valley aquifer system. *A*, Concept of aquifers used in many hydrologic reports of the Central Valley; Sacramento Valley (adapted from Bloyd, 1978); and San Joaquin Valley (adapted from Poland and Lofgren, 1984). *B*, Concept of single heterogeneous aquifer with varying vertical leakance and confinement (adapted from Williamson and others, 1989).

chapter D (Williamson and others, 1989). The simulation utilized the U.S. Geological Survey's three-dimensional finite-difference model (Trescott, 1975; Trescott and Larsen, 1976). The model was modified to include a procedure first described by Meyer and Carr (1979) that simulates the effects of land subsidence due to inelastic compaction of clays (Prudic and Williamson, 1986). The resulting model considers the valley deposits as one aquifer system characterized by variations in vertical leakage properties. The leakage depends not only on the vertical permeability of the sediments, but also on the density of wells constructed with long perforated sections or multiple screens, because such wells provide vertical hydraulic connection within the aquifer system.

Four aquifer layers were specified within the model: an upper layer representing the shallow water-table zone, two middle layers representing the lower pumped zone, and a basal layer representing the continental deposits below the deepest wells in the valley (fig. 9). The model simulated recharge from precipitation, streams, and irrigation returns and simulated discharge to streams, evapotranspiration, and wells. Emphasis was placed on simulation of the period from 1961 to 1977 because of availability of data and because this period was representative of long-term climatic conditions including wet years and dry years. The discussion of regional ground-water flow presented here draws heavily on the results of simulation by Williamson and others (1989).

The natural pattern of ground-water movement and the rates of recharge and discharge have been significantly altered by water development. Prior to development, ground water generally moved from recharge areas in the higher ground surrounding the Central Valley toward topographically low areas in the center of the valley. The general pattern of lateral flow in the valley before development is shown by the water-table contour map in figure 11. Note that ground water flowed largely toward the Sacramento or San Joaquin Rivers except in the southern San Joaquin Valley, where flow was toward Tulare Lake.

Recharge was supplied primarily by streams entering the valley from the Sierra Nevada and Klamath Mountains and, to a lesser extent, directly from precipitation. The streamflow (mostly snow meltwater) was largest from January to June. Recharge via stream channels took place mostly in their upper reaches shortly after entering the valley. Downward hydraulic gradients undoubtedly were present in these recharge areas, but they are not well documented because of the scarcity of data from older deep wells.

Prior to irrigation development, most ground water was discharged as evapotranspiration in the central trough of the valley, and to a lesser extent, it was discharged to streams. Potential evapotranspiration in the valley's center is about 49 in/yr, exceeding precipitation rates. The occurrence of upward direction of hydraulic gradients in the central part of the valley is shown by the large area of flowing wells that were documented prior to 1900 (Hall, 1889; Mendenhall and others, 1916). In the southern San Joaquin Valley, ground water was discharged to Tulare Lake and as evapotranspiration in the area surrounding it (shown by the closed depression in fig. 11). Water discharging to stream channels flowed into the Sacramento and San Joaquin Rivers, then into the Delta and westward into San Francisco Bay.

The regional hydraulic gradients in the aquifer system were steeper in the Sacramento Valley than in the San Joaquin Valley for the following reasons: (1) The outlet at the confluence of the Sacramento and San Joaquin Rivers is closer to the northern end of the Central Valley, (2) recharge rates were higher in the Sacramento Valley, and (3) average permeabilities are lower in the Sacramento Valley.

The ground-water flow system has been greatly altered by large-scale ground-water development and very large diversions and redistribution of surface water through the Central Valley. Heavy pumpage from wells, averaging 11.5 million acre-ft annually during the 1960's and 1970's, combined with increased recharge due to irrigation returns from redistributed surface water, caused changes in ground-water levels throughout most of the Central Valley. Examples of long-term ground-water-level changes in some wells caused by the water development are shown in figure 12.

The configuration of the water table in 1976 (fig. 13) shows the effects of heavy pumpage from wells. Ground water now flows primarily toward cones of depression at pumping centers rather than toward the preexisting natural discharge areas along the Sacramento and San Joaquin Rivers and around Tulare Lake, but there is still a large component of flow toward the Delta area. The largest ground-water-level declines have occurred in the western and southern parts of the San Joaquin Valley. Declines are much less in the Sacramento Valley, but a major pumping depression has formed just north of the Delta. Recharge from irrigation returns has caused ground-water levels to rise above their predevelopment levels in parts of northwestern San Joaquin Valley and parts of central Sacramento Valley. (See further discussion of water-level declines in the section "Effects of Ground-Water Withdrawal on the Central Valley Aquifer System.")

The combination of increased recharge to the water table and increased pumping from the lower zone has caused a reversal in the direction of the hydraulic gradient (from upward to downward) in the center of the Central Valley (Williamson and others, 1989). Large

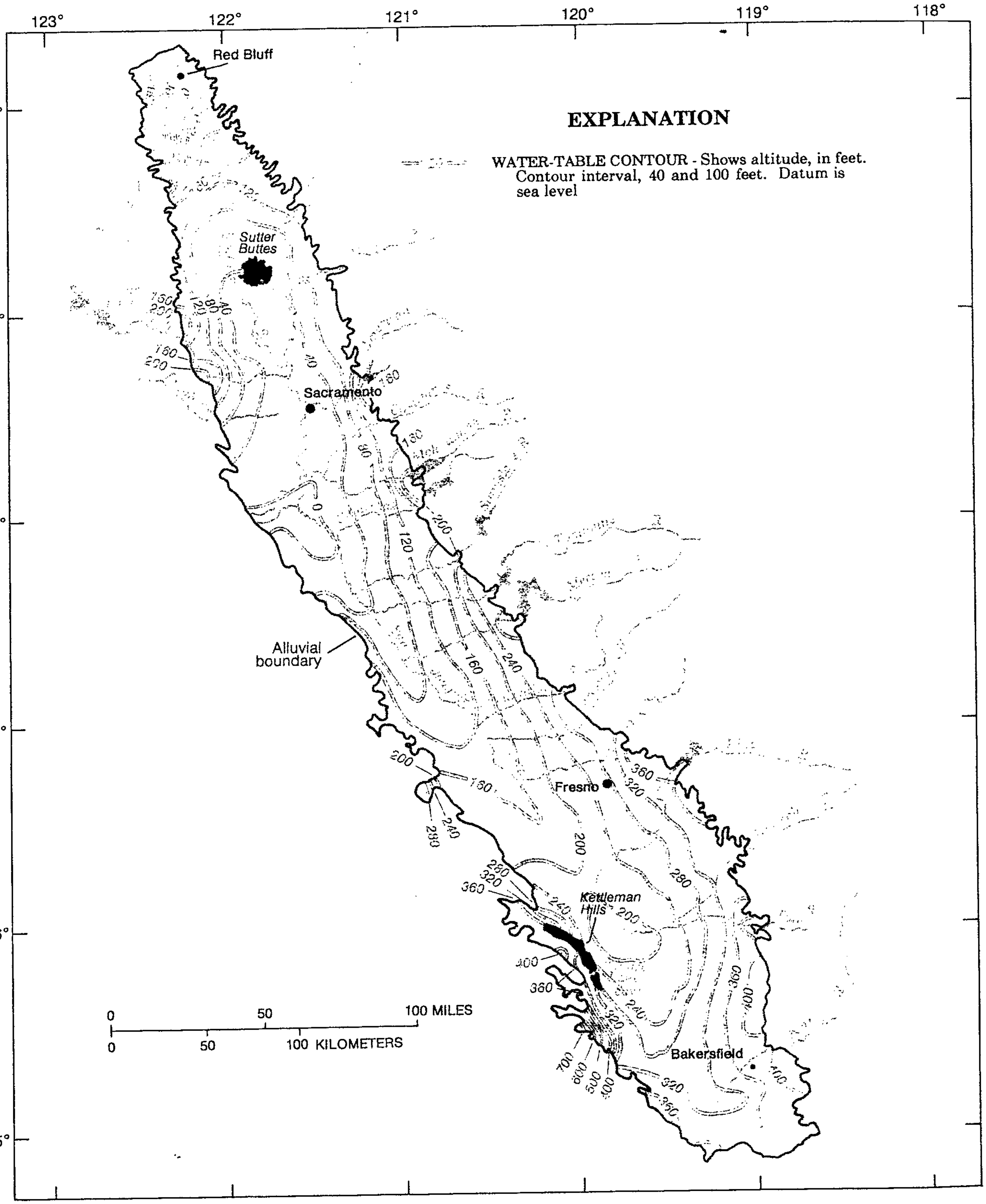

FIGURE 11.—Estimated predevelopment water table (modified from Williamson and others, 1989).

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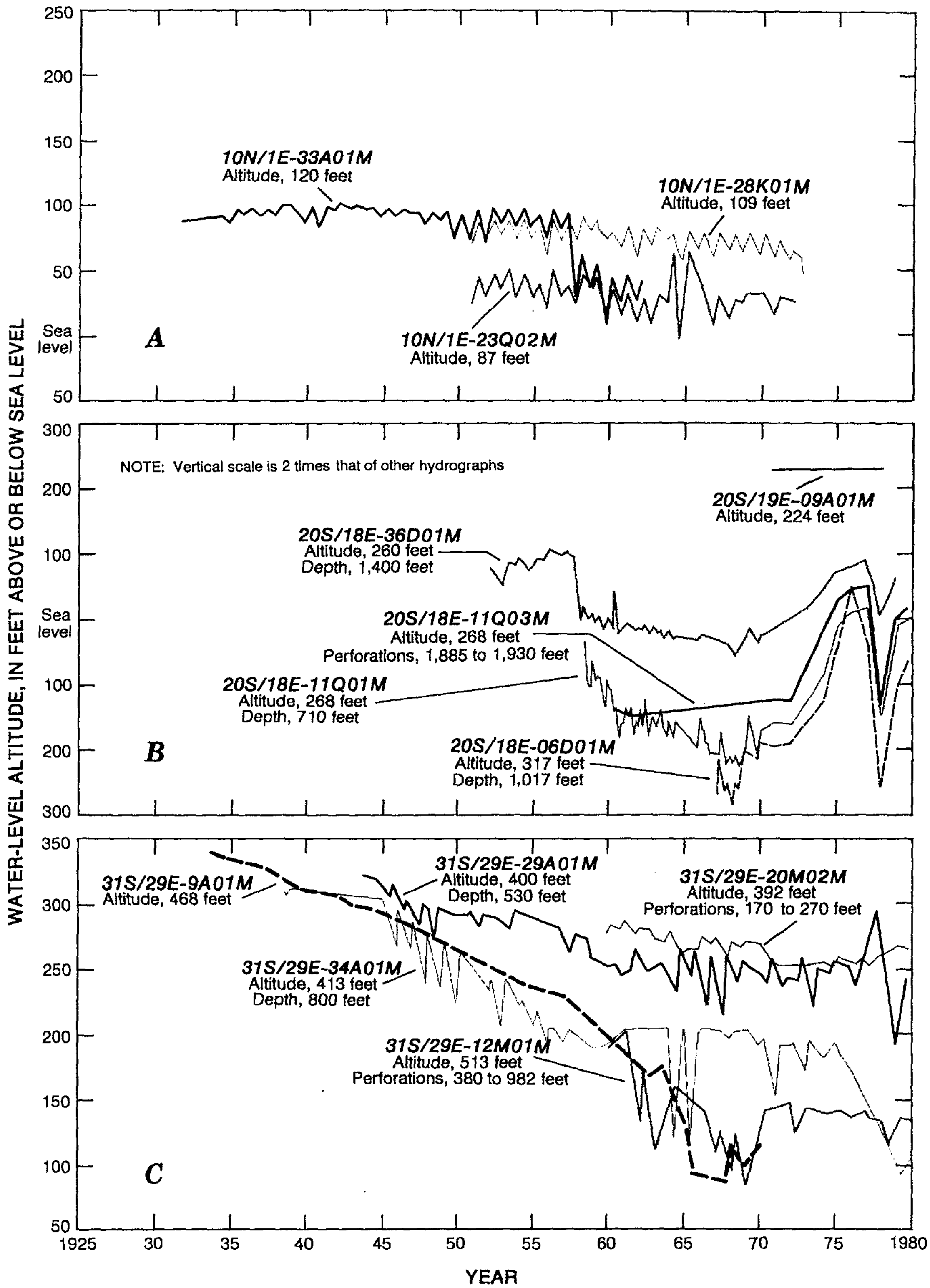

FIGURE 12.—Representative hydrographs showing long-term changes in ground-water levels in the Central Valley (modified from Williamson and others, 1989). See figure 5 for well-numbering system. *A*, Wells in Central Valley near Woodland. *B*, Wells on west side of San Joaquin Valley north of Kettleman City. *C*, Wells in southern San Joaquin Valley near Bakersfield.

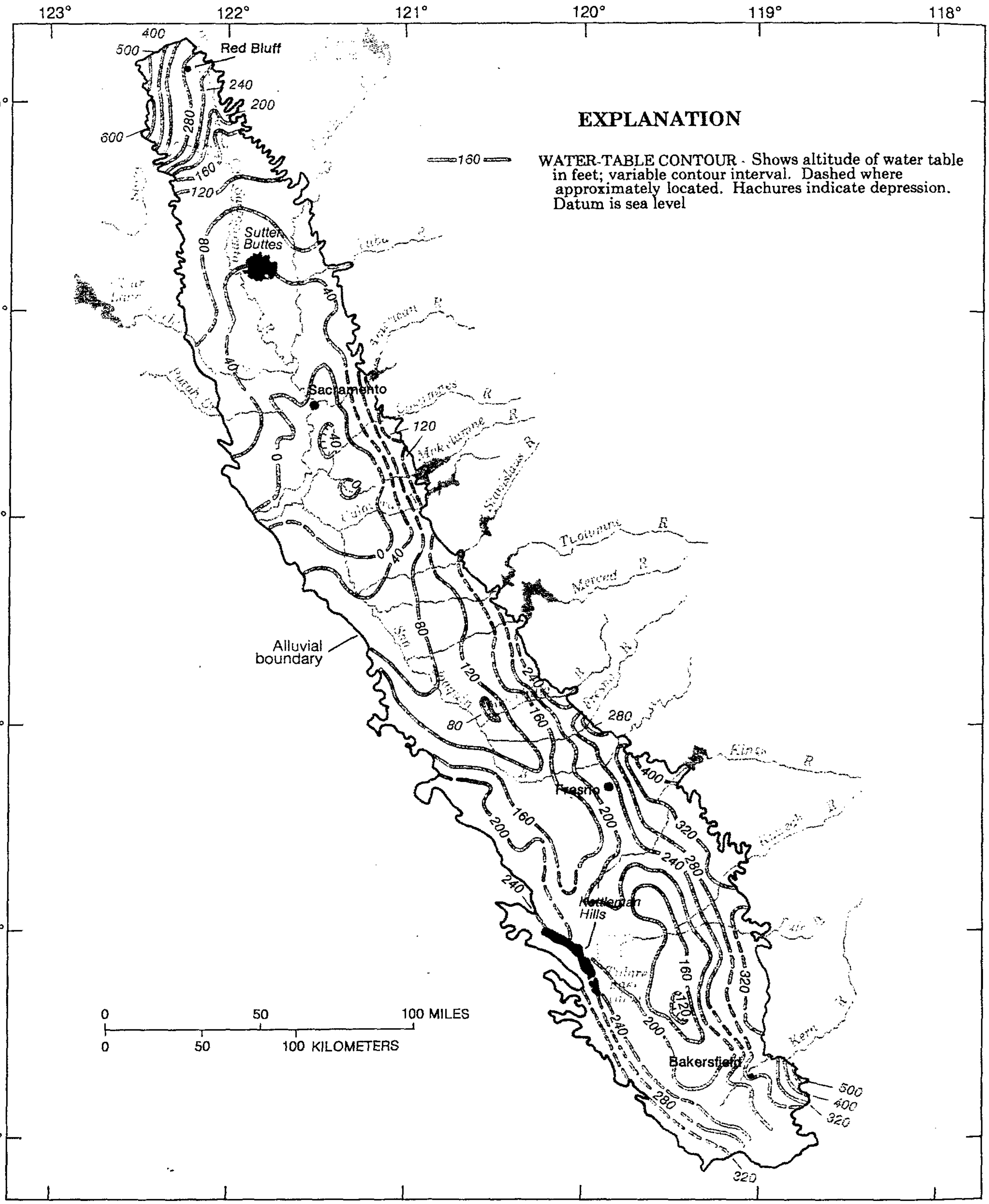

FIGURE 13.—Water table in 1976 (modified from Williamson and others, 1989).

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withdrawals of ground water from the west side of the San Joaquin Valley have profoundly affected hydraulic gradients and flow patterns there. The heads in the lower zone (originally above land surface) are now below sea level and the direction of lateral ground-water flow has been reversed (Bull and Miller, 1975). Water in the lower zone previously flowed toward the center of the valley and discharged in the slough near the San Joaquin River (fig. 14). However, by the 1960's, flow was mostly toward the pumping center on the west side of the valley.

The total flow through the aquifer system has increased from about 2 million acre-ft/yr prior to development to nearly 12 million acre-ft/yr after development (Williamson and others, 1989). The increased pumpage is supplied largely by increased recharge, mostly from imported surface water or recirculated pumped water. Increased pumpage of ground water has not only changed the amount of regional flow, it has also decreased the amount of water in storage and caused the land surface to subside over a large area. These effects are discussed in the section "Effects of Ground-Water Withdrawal on the Central Valley Aquifer System."

GROUND WATER IN STORAGE

The quantity of water in storage in the aquifers of the Central Valley has been estimated by several investigators. All such estimates are based on use of average values of specific yield for different lithologies and an arbitrary thickness of the aquifer system. Earlier investigators restricted their estimates to the shallow part of the aquifer system. Olmsted and Davis (1961) estimated that there were 28 million acre-ft of water in storage in the upper 200 ft of sediments in the Sacramento Valley.

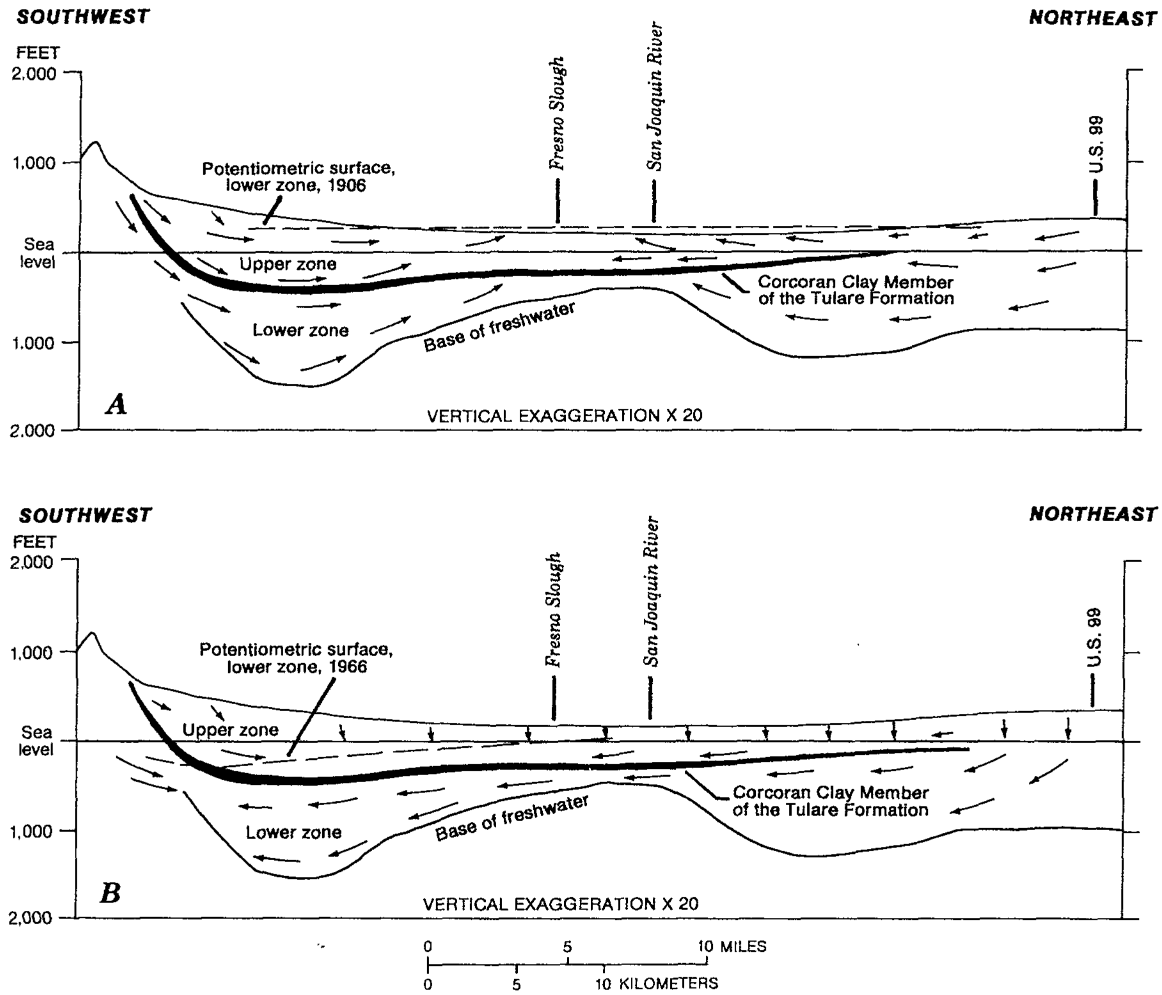

FIGURE 14.—Predevelopment and current ground-water flow conditions (shown by arrows) in the San Joaquin Valley (from Bull and Miller, 1975, fig. 20). *A*, About 1900. *B*, 1966.

This estimate was based on dividing the sediments into four lithologic groups (channel deposits, alluvial plain and fan deposits, dissected alluvial deposits, and valley deposits) and assigning storage characteristics to each group. Davis and others (1959) estimated that there were 121 million acre-ft in the upper 200 ft of the aquifer system in the San Joaquin Valley.

As part of this RASA study, Williamson and others (1989) estimated that there were about 830 million acre-ft of freshwater in the upper 1,000 ft of the continental deposits in the Central Valley (as of 1961). This estimate was derived from a study of several thousand well logs, in which values of specific yield were assigned to depth intervals according to texture as mapped by Page (1986). Average values of specific yield for designated aquifer layers and subareas were then computed and are given in table 7 of Williamson and others (1989). The thickness of the aquifer system was taken as the difference between the 1961 water table and the lesser of either the depth to base of freshwater, or depth to the base of continental deposits, or 1,000-foot depth. The product of the specific yields and thicknesses, so derived, provided values of ground water in storage as follows:

Area	*Average specific yield*	*Volume of ground water in storage (million acre-ft)*
Sacramento Valley	0.07	170
Delta	0.08	130
San Joaquin Valley	0.10	160
Tulare Basin..............	0.10	370
Central Valley	0.09	830

As discussed in the section "Effects of Ground Water Withdrawal on the Central Valley Aquifer System," ground water in storage was depleted at an average rate of 800,000 acre-ft annually during the 1960's and 1970's. Thus, the total ground water in storage as of 1986 was probably about 810 million acre-ft.

GROUND-WATER DEVELOPMENT

HISTORY OF DEVELOPMENT

Ground-water development began in the Central Valley about 1880. However, development of surface water, primarily for irrigation, had been underway for the previous 100 years. By 1900, an extensive system of canals had been built to supply surface water to the southern San Joaquin Valley, and ground water was providing only a very small part of the irrigation water.

After 1900, the construction of wells and rate of ground-water withdrawal increased slowly. By 1913, total well pumpage for the Central Valley was estimated to be 360,000 acre-ft annually. During the 1940's and 1950's, the pumpage of ground water for irrigation increased sharply. During the 1960's and 1970's, ground-water pumpage averaged about 11.5 million acre-ft/yr and was providing about 50 percent of the water used for irrigation. This withdrawal rate represented about 20 percent of the total yearly ground-water pumpage in the United States during that time. Pumpage for domestic and industrial use rose slightly during the 1960's and 1970's, but by 1977, it constituted only 5 percent of the total ground-water withdrawal. A summary of ground-water pumpage in the Central Valley from 1961 to 1977 was provided by Diamond and Williamson (1983).

In the late 1960's, increased importation of surface water in some areas caused ground-water pumpage to decline and many wells to be unused. However, a drought in 1976 and 1977 decreased the availability of imported surface water, and ground-water pumpage increased sharply, reaching a maximum of 15 million acre-ft in 1977. Thus, in recent years, annual ground-water pumpage has fluctuated depending upon the availability of imported surface water. The areal distribution of the relatively light ground-water pumpage during the wet year of 1975 is compared with the heavy pumpage during the drought year of 1977 in figure 15.

During the early 1980's, ground-water pumpage decreased slightly from the 11.5 million acre-ft annual rate of the 1960's and 1970's, and the 1980's pumpage is about equal to the estimated recharge. Pumping in the Central Valley is seasonal, and most of the water is withdrawn during the spring-summer growing season. The autumn-winter period is usually a period of water-level recovery. Historically, the highest withdrawal rates have been in the drier areas—the south-central part of the San Joaquin Valley.

DEPTH AND YIELD OF WELLS

Most of the (approximately) 100,000 high-capacity wells in the Central Valley are used for either irrigation or public water supply. Yields in excess of 1,000 gal/min are generally required and can be obtained nearly everywhere. The depth at which such yields can be obtained, however, varies depending on the local geology. Poor-quality water at shallow depths in some areas requires deep wells.

Well depths in the Sacramento Valley are generally less than those in the San Joaquin Valley, and they range from an average depth of 120 ft in the highly permeable areas to nearly 500 ft in the less permeable areas. An analysis of performance tests on 2,783 wells reported by Olmsted and Davis (1961) indicated that most of those wells yielded 250 to 1,700 gal/min. For these wells, specific capacities ranged from about 20 to 100 (gal/min)/ft of drawdown, and the saturated thickness tapped ranged from about 100 to 400 ft.

Well depths in the San Joaquin Valley range from about 100 to 3,500 ft. The deepest wells are in the west-central and south-central parts of the valley, where the primary source of water is the lower zone. Elsewhere in the San Joaquin Valley, most wells tap the upper zone. For example, in the eastern part of the Los Banos-Kettleman City area, Bull and Miller (1975) noted that wells tapping the highly permeable upper-zone sands may be only 150 to 200 ft deep and yield 1,500 gal/min. In the western part of that area, however, where the upper zone has low permeability, wells must be 2,500 to 3,500 ft deep to obtain adequate yields (900 to 1,200 gal/min).

Davis and others (1964) summarized data from 15,000 well-performance tests in the San Joaquin Valley. They noted that most wells yielded 500 to 1,500 gal/min with specific capacities ranging from 10 to 100 (gal/min)/ft of drawdown.

EFFECTS OF GROUND-WATER WITHDRAWAL ON THE CENTRAL VALLEY AQUIFER SYSTEM

The effects of ground-water withdrawal on the Central Valley aquifer system were investigated by computer simulations of ground-water flow prior to and following development as described in chapter D (Williamson and others, 1989). As noted earlier, the valley deposits (clay, silt, sand, and gravel) were simulated as one aquifer system characterized by variations in vertical leakance properties. The leakance depends not only on the vertical permeability of the sediments but also on the density of wells and their construction. Many of the wells are constructed with long intervals of perforated casing that connect several aquifer layers and thus greatly increase the vertical hydraulic connection through the aquifer system.

CHANGES TO THE GROUND-WATER FLOW SYSTEM

Before ground-water development, the flow system of the Central Valley was in a state of dynamic equilibrium—natural recharge was balanced by natural discharge (fig. 16). As described earlier, ground water flowed toward the axial part of the valley and discharged primarily as evapotranspiration from marshes that existed prior to development. Some discharge also occurred along stream channels where aquifer heads were higher than stream stages. The total flow through the aquifer system was small (about 2 million acre-ft/yr) compared to the surface-water inflow (about 32 million acre-ft/yr). Total precipitation in the valley was estimated to be 12.4 million acre-ft/yr, and total evapotranspiration directly from precipitation was estimated to be 10.9 million acre-ft/yr, leaving 1.5 million acre-ft/yr of water to recharge the aquifer system.

The construction of about 100,000 irrigation wells and annual ground-water withdrawals of about 11 million acre-ft during the 1960's and 1970's, together with greatly increased recharge from irrigation returns (derived from imported surface water and recirculated pumped water), have significantly altered the ground-water flow pattern of the Central Valley aquifer system. Because ground-water pumpage and recharge from irrigation water since the 1960's has greatly exceeded the estimated predevelopment recharge rate (fig. 16), flow is largely from areas recharged by imported irrigation water toward areas of irrigation pumpage. Flow through the aquifer system increased nearly sixfold—from about 2 to nearly 12 million acre-ft/yr. The values shown in figure 16 do not include water that recharged the aquifer system only to be discharged a short distance away. Thus, total ground-water flow during the 1960's and 1970's, which represents both regional and local flow systems, was greater than that presented in figure 16. Simulation suggests that downward flow from the shallow deposits and from the upper part of the lower pumped zone has increased by an order of magnitude (Williamson and others, 1989).

Water during the 1960's and 1970's was supplied principally by irrigation returns and, to a lesser extent, by natural recharge and by continuing depletion of aquifer storage. However, during the early 1980's, ground-water pumpage decreased slightly and was about equal to the combined rate of natural recharge and irrigation returns. Direct evapotranspiration from the ground-water reservoir was almost completely eliminated owing to lowering of the water table.

The aquifer system's ability to transmit water vertically has changed in direct response to the construction of about 100,000 irrigation wells (fig. 17). Most of the wells in the Central Valley contain perforated casing throughout their lower two-thirds (Diamond and Williamson, 1983). Where the Corcoran Clay Member is present, the perforated sections of many wells fall above and below this confining unit to provide direct hydraulic connection vertically through the perforated zone. Vertical flow is substantial inside many unpumped wells. On the basis of current-meter traverses in 16 wells, Davis and others (1964) concluded that vertical flow through about 3,000 wells that pierced confining beds was about 100,000 acre-ft/yr in the western part of the San Joaquin Valley. Probably an even greater amount of flow occurs through wells in the rest of the Central Valley (Williamson and others, 1989).

Conversely, decreased vertical flow through the confining beds probably resulted from the inelastic compac-

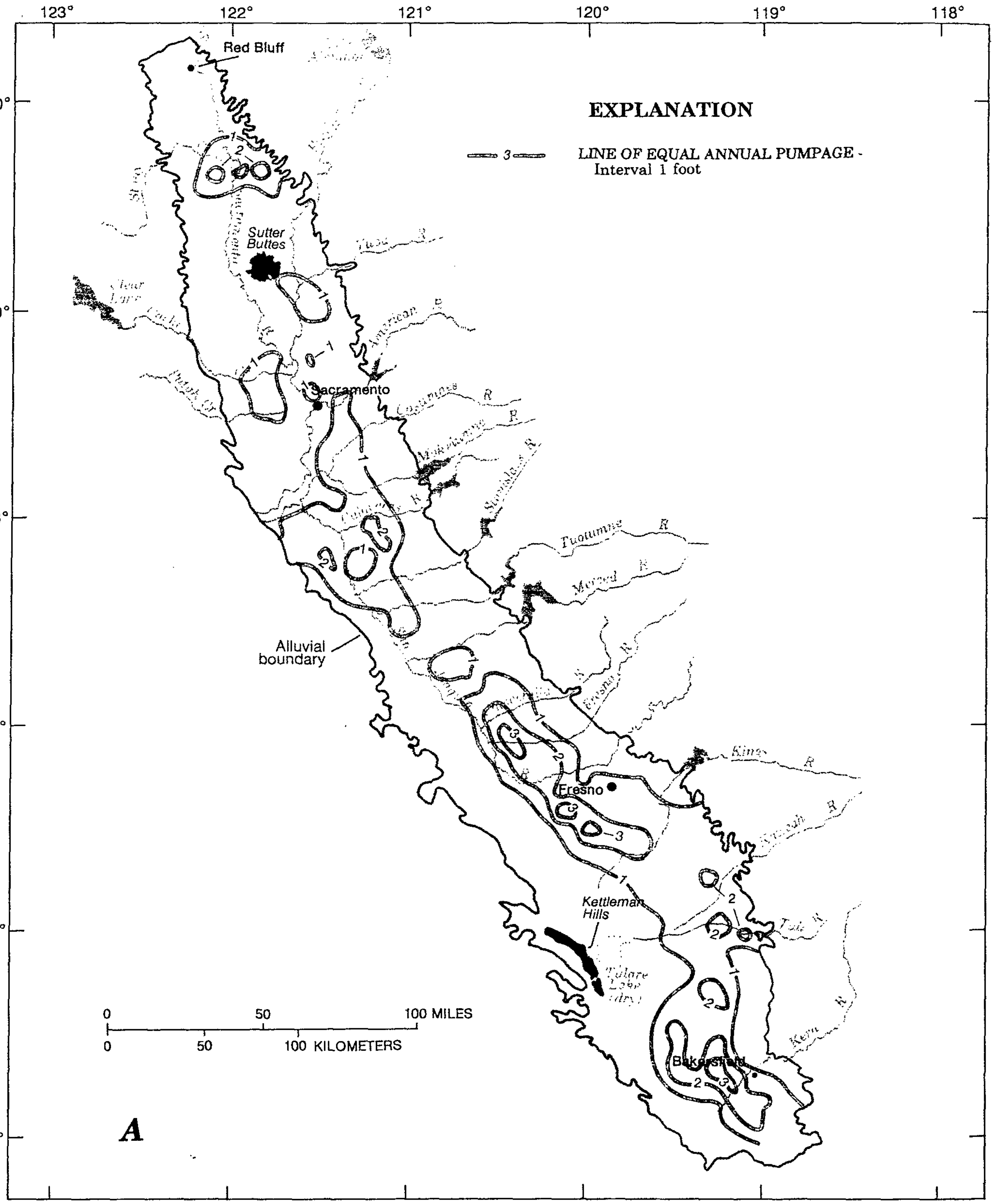

FIGURE 15.—Ground-water pumpage in the Central Valley for 1975 and 1977 (modified from Williamson and others, 1989). *A*, 1975 (wet year). *B*, 1977 (drought year).

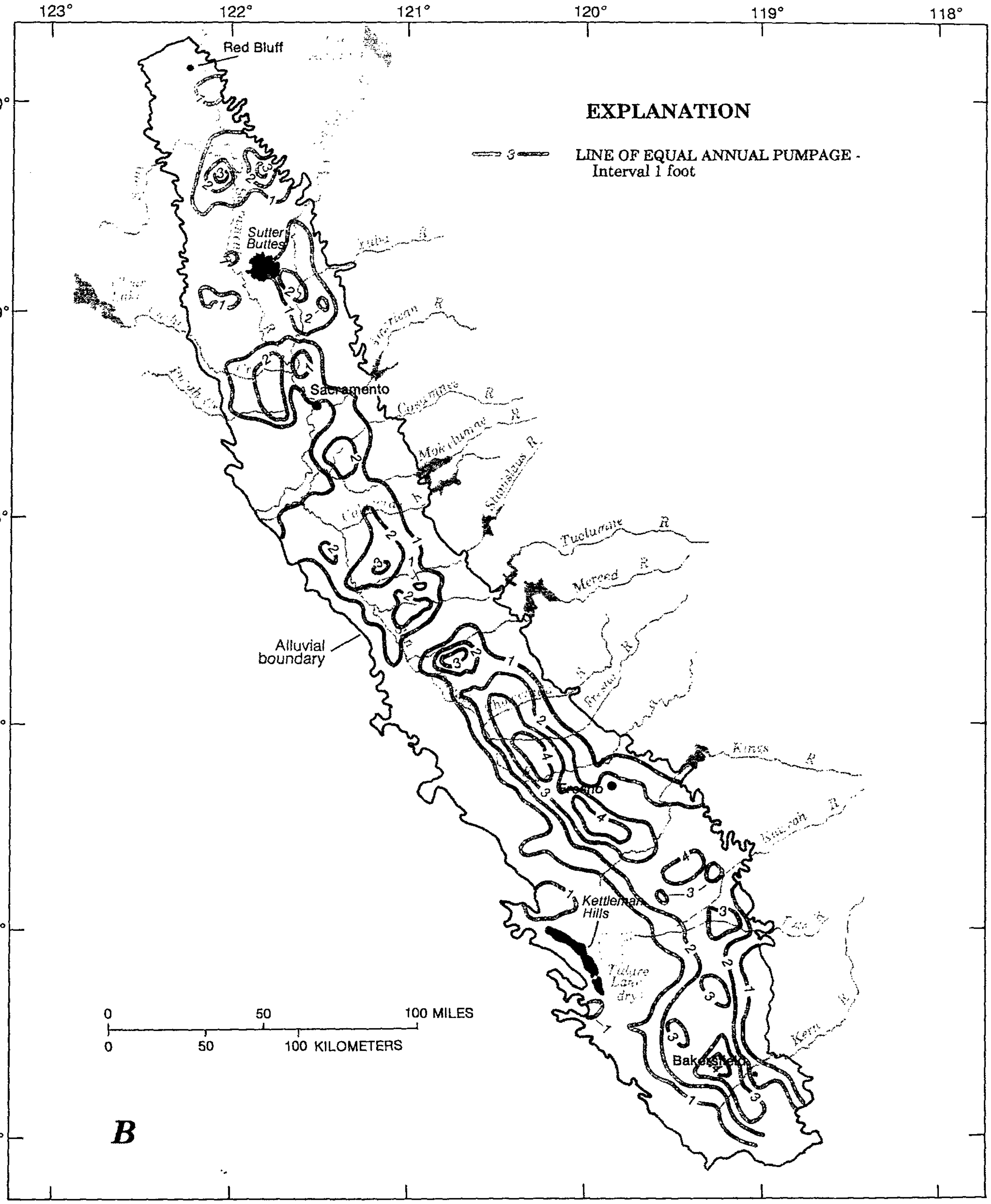

FIGURE 15.—Continued

tion of fine-grained materials within the aquifer system. Thus, the vertical permeability of the Corcoran Clay Member and the many clay beds in the section may have been reduced by 1.5 to 6 times (Williamson and others, 1989).

Changes in the aquifer system's vertical flow were investigated with the finite-difference flow model as described in chapter D (Williamson and others, 1989). Simulations suggest that the average vertical leakance increased by about an order of magnitude from the predevelopment era to the 1970's. This increase is due to the large number of wells that contain long intervals of perforated casing (fig. 17). In some areas of the valley, the simulated increase in vertical leakage was more than three orders of magnitude. Such localized, very large increases are most logically explained by vertical movement of water through many wells. Simulations intended to determine possible decreases in vertical leakance due to inelastic compaction of clays were inconclusive because of the dominant effect of vertical flow through unpumped wells.

Calculations presented in chapter D indicate that if large-diameter wells perforated over a long interval are evenly distributed, the vertical leakance of one well is about the same as that of the fine-grained beds in about 7 mi^2 of the aquifer system. Therefore, in areas with many wells, the vertical flow is significantly altered by well density.

CHANGES IN AQUIFER STORAGE

Ground-water levels have been significantly altered by development in the Central Valley (fig. 12). For the most part, long-term declines of the water table are less than 100 ft except locally in the southern part of the San Joaquin Valley. In a few areas, increased recharge from irrigation returns has caused the water table to rise as

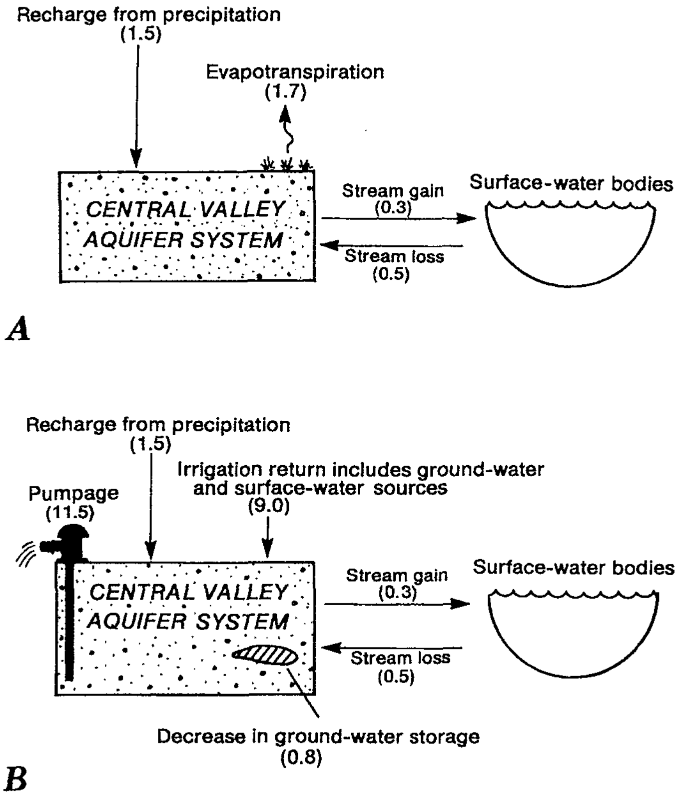

FIGURE 16.—Change in regional ground-water flow system due to development (all values in millions of acre-feet per year). *A*, Predevelopment. *B*, Average rates during 1960's and 1970's.

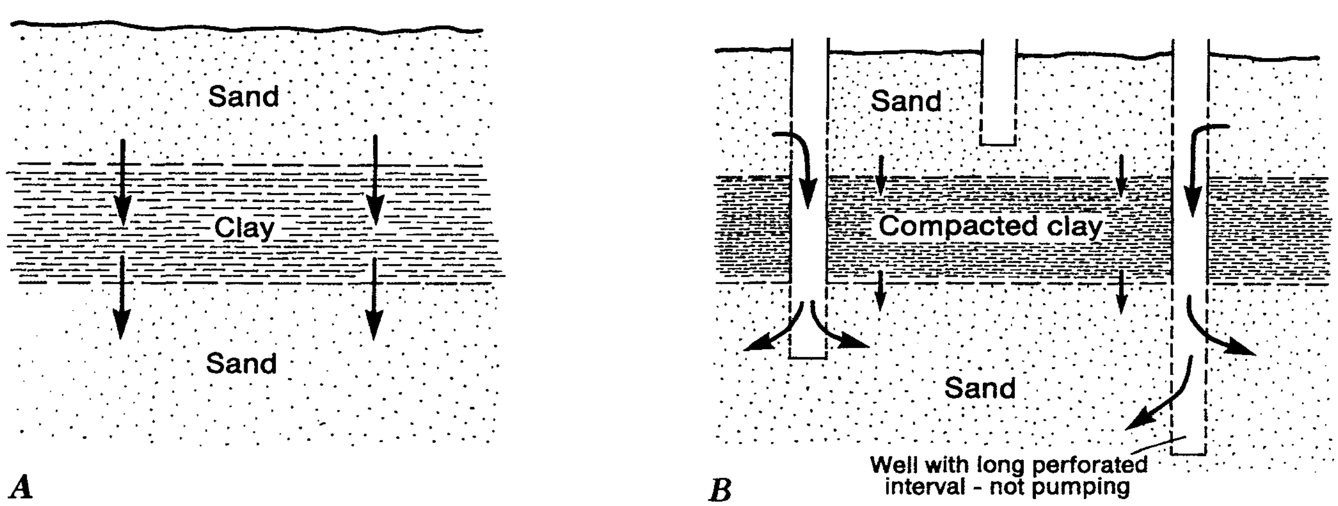

FIGURE 17.—Change in effective vertical conductance of Central Valley aquifer system due to development; size of arrows represents relative magnitude of flow. *A*, Predevelopment effective vertical conductance. *B*, Current effective vertical conductance.

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much as 40 ft. Head declines in the lower pumped zone in the Sacramento and northern San Joaquin Valleys generally are small—less than 80 ft (fig. 18). However, in the heavily pumped western and southern parts of the San Joaquin Valley, heads have declined from 100 to 400 ft since development began. Since the late 1960's, the increased availability of imported surface water in these areas and the accompanying decrease in ground-water pumpage has stopped the long-term decline and allowed some recovery of ground-water levels. Year-to-year changes in ground-water levels have reflected the availability of surface water. During wet or average years, more imported surface water is available for irrigation; as a result, well pumpage decreases and ground-water levels rise. During drought years, such as 1976 and 1977, less surface water is available, wells are more heavily pumped, and ground-water levels decline.

When heads have declined sufficiently in the lower pumped zone for inelastic compaction of clay beds to occur, the rate of water-level decline slows. This slower rate results because the effective storage coefficient is significantly increased (Williamson and others, 1989).

The result of the decline in ground-water levels from the start of development until 1977 has been the loss of an estimated 60 million acre-ft of aquifer storage. This depletion of storage is made up of three components.

1. Long-term lowering of the water table that results from dewatering of the shallow sediments—40 million acre-ft.
2. Inelastic compaction (permanent reduction of pore space)—17 million acre-ft.
3. Elastic storage (compression of sediments and expansion of water)—3 million acre-ft.

The changes in storage were calculated with the computer model as described in chapter D (Williamson and others, 1989). The decrease in storage due to dewatering is the product of specific yield, water-table decline, and area of the shallow aquifer dewatered. Similarly, the change in elastic storage is the product of elastic specific storage, thickness of confined aquifer, head decline, and area of aquifer affected.

The loss of storage from inelastic compaction of clay beds causes a permanent loss of pore space that in turn is balanced by an equivalent volume of land subsidence (see next section). Extensive leveling by the National Geodetic Survey over many years has established the extent of land subsidence in the Central Valley (Poland and others, 1975; Ireland and others, 1984). The 17 million acre-ft of storage loss attributed to inelastic compaction of fine-grained sediments is simply the volume of land subsidence derived from these surveys.

During the 1960's and 1970's, the annual decrease in ground-water storage was about 800,000 acre-ft, representing about 7 percent of annual pumpage (fig. 16). The long-term decrease in aquifer storage of 60 million acre-ft, although very large, represents only a small part of the more than 800 million acre-ft of freshwater stored in the upper 1,000 ft of sediments in the Central Valley. Nevertheless, the lowering of water levels in the upper and lower zones caused a significant increase in pumping lifts and thus a significant increase in the cost of pumping ground water. During the early 1980's, ground-water pumpage decreased, ground-water levels rose in many areas, and there was virtually no further decrease in ground-water storage.

LAND SUBSIDENCE

The largest volume of land subsidence in the world caused by human activities is in the Central Valley. The area affected by subsidence includes much of the southern part of the San Joaquin Valley and smaller areas in the Sacramento Valley and the Delta (fig. 19). By far, the largest volume of land subsidence is caused by ground-water pumpage and the resulting compaction of clay in the San Joaquin Valley. However, other processes have contributed to land subsidence locally as described by Poland and Evenson (1966) and Poland and Lofgren (1984). Briefly, the five processes that cause subsidence are:

1. Compaction of fine-grained sediments in the aquifer system resulting from head declines due to heavy ground-water pumpage.
2. Compaction of sediments in petroleum reservoir rocks caused by oil and gas extraction.
3. Hydrocompaction—compaction of moisture-deficient sediments following the first application of water.
4. Compaction of peat soils following land drainage.
5. Tectonic subsidence.

Compaction of peat soils and subsequent land subsidence has occurred in an area of about 450 mi^2 in the Delta area formed at the confluence of the San Joaquin and Sacramento Rivers (Poland and Evenson, 1966). Islands in the Delta area that were originally at or slightly above sea level are now 10 to 20 ft below sea level. This type of subsidence results from oxidation and compaction of peat soils following drainage of marshlands for agriculture. This area was drained in the middle and late 1800's, which resulted in subsidence that is continuing today. Increased pumping is required to maintain a lowered water table for cultivation.

Hydrocompaction refers to the compaction of moisture-deficient deposits above the water table following the

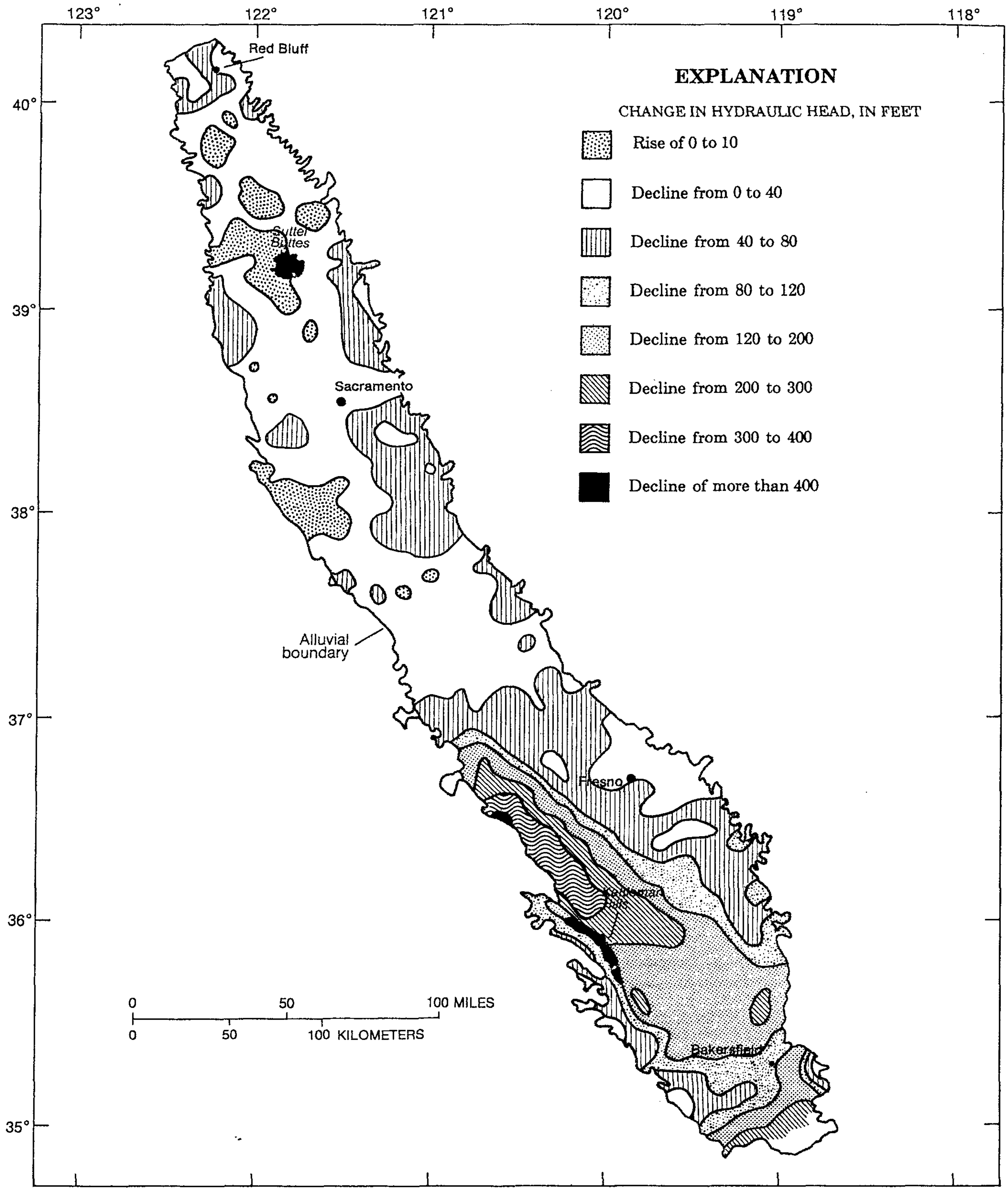

FIGURE 18.—Estimated change in hydraulic head in lower pumped zone from 1860 to 1961 (modified from Williamson and others, 1989).

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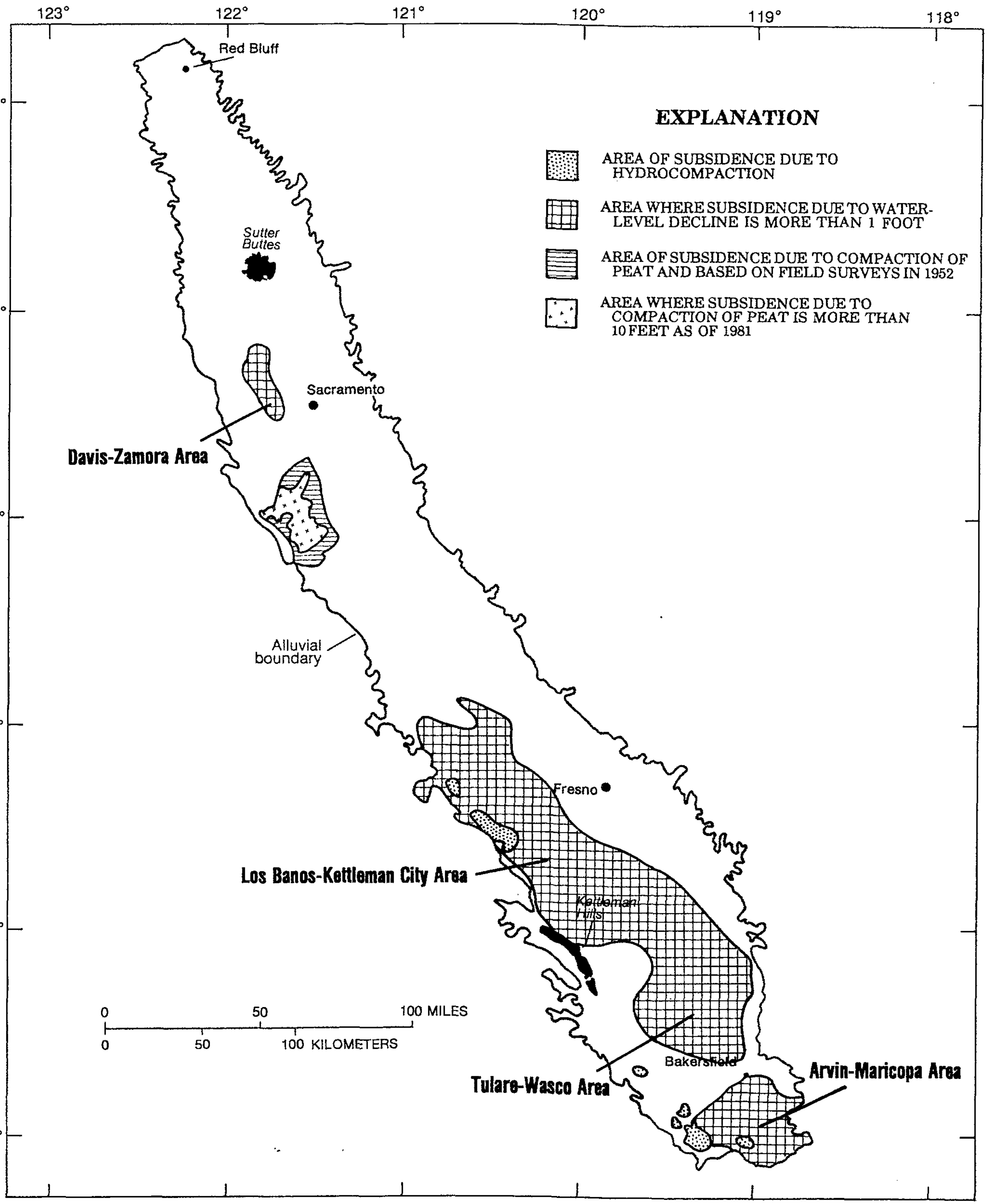


FIGURE 19.—Areal extent of land subsidence in the Central Valley (modified from Williamson and others, 1989).

first application of water. Dry areas along the west and south margins of the San Joaquin Valley have subsided in such a manner (fig. 19). Within these areas, subsidence of 5 to 10 ft is common (Poland and Evenson, 1966).

Compaction of sediments due to the withdrawal of oil and gas has caused land subsidence locally; however, the magnitude is uncertain. Subsidence of less than 1 ft has been attributed to this process in the oil fields near Bakersfield by Lofgren (1975).

Subsidence due to tectonic movement has been negligible compared to the other four processes during the last 100 years, according to Williamson and others (1989).

Land subsidence in California due to ground-water withdrawal has been extensively studied by the U.S. Geological Survey since the mid-1950's. The pioneer work by Geological Survey hydrologist Joseph F. Poland and his colleagues established many of the principles of the mechanics of land subsidence as well as field measurement techniques. Their studies were reported largely in U.S. Geological Survey Professional Papers. Areal investigations of land subsidence are described in Professional Paper 437, chapters A–I. Studies of the geology, physical properties, and compaction mechanisms of sediments in subsiding areas are described in Professional Paper 497, chapters A–G.

The principal field methods used to determine the magnitude of land subsidence in California have been extensometer wells and precise leveling. A network of bench marks was established and precise leveling was done by the National Geodetic Survey as well as State and municipal government agencies. Extensometer wells were used to measure the change in thickness of the compacting sediments. Such wells consist of a heavy weight anchored into the formation below the bottom of the well casing and a cable attached to the weight on one end and a counterweight at the other end. A recorder provided continuous measurement of the movement of the land surface with respect to the anchor weight. For a summary of field methods to measure land subsidence, the interested reader is referred to a UNESCO guidebook on land subsidence (Poland, 1984).

Mechanics of Land Subsidence

Land subsidence due to withdrawal of ground water is caused by compaction of clay within an aquifer system. When pumpage causes the hydraulic head to decline below the preconsolidation stress level, the effective stress (grain-to-grain load) increases and the clay is compacted, releasing water to the aquifer system. A brief summary of the mechanics of land subsidence is given here. This discussion is based largely on detailed analysis of the stresses involved in land subsidence as presented by Lofgren (1968) and Poland (1984, p. 37–54).

The classic equation for effective stress (originally developed by Karl Terzaghi and described in Terzaghi and Peck, 1967) is as follows:

$$P' = P - u_w$$

where

- P' is effective stress (effective overburden pressure or grain-to-grain load),
- P is total stress (geostatic pressure), and
- u_w is pore pressure (fluid pressure).

As the hydraulic head is reduced in a confined aquifer (sand and (or) gravel), the geostatic pressure is not significantly changed. Thus, the decreased pore pressure causes increased grain-to-grain load. The compaction of the aquifer is small, immediate, and largely recoverable. However, for confining beds (clay and silt) with much lower permeability but higher specific storage, the response is quite different. The adjustment of pore pressure in the confining beds to head decline in the aquifer proceeds slowly (after months or years). Compaction is substantial and largely unrecoverable. If pumping ceases, heads recover, and compaction of the confining beds eventually ceases (though it may continue for some time). If pumping resumes, the confining beds will not be compacted until the head declines below the head (critical head, fig. 20) of the previous pumping period (providing the compaction was completed during the previous pumping period). The loss of inelastic storage from the compacting clay is not recoverable. The recovery of heads to prepumping levels is not accompanied by a recovery of storage lost to compaction.

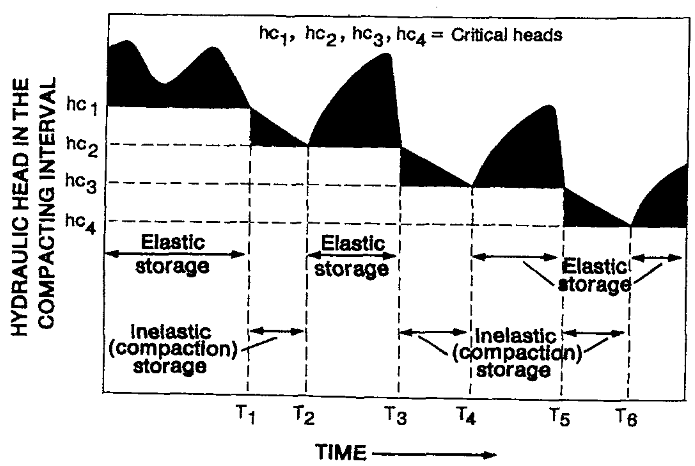


FIGURE 20.—Relation of ground-water storage to hydraulic head in a compacting aquifer system (modified from Prudic and Williamson, 1986).

The relation of storage and hydraulic head in a compacting aquifer system is shown in figure 20. Note that head declines are rapid when pumped water is derived from elastic storage but are slow when it is derived from inelastic storage.

Water derived from compaction has varied from a few percent to more than 60 percent of the pumped water in the subsiding areas. These differences were attributed to variations in geology and well construction, as discussed in chapter C (Page, 1986), and are summarized here. The percentage of fine-grained deposits within the stressed interval and the mineralogy of these deposits are important factors. In the Los Banos-Kettleman City area, an area of maximum land subsidence, the highest percentage of fine-grained deposits anywhere in the San Joaquin Valley lies within the upper 2,000 ft of the aquifer system. Bull (1975, p. F49) suggested that within this area, interlayering of thin-bedded, compressible fine-grained sediments with permeable coarse-grained sediments resulted in rapid and substantial compaction in response to water-level declines. Compaction is less with the same water-level declines in areas of coarse-grained beds.

The type of clay mineral present influences subsidence; montmorillonite is highly susceptible to compaction and is the predominant clay mineral in the major subsiding areas of the San Joaquin Valley. Differences in hydraulic head throughout the pumped interval also affect compaction; the rate of compaction is less when the water table and artesian head are lowered simultaneously, as in a well that is perforated in both water-table and confined zones.

The factors influencing inelastic compaction and land subsidence are summarized in figure 21. Where wells are perforated in confined zones of an aquifer system that contain numerous thin lenses of compressible montmorillonite clay, inelastic compaction will be at a maximum. However, where wells tap both water-table and confined zones and much of the perforated section falls within coarse-grained deposits, compaction will be minimal.

The measured compaction in relation to head decline at two wells in subsiding areas from 1960 to 1980 is shown in figure 22. At each site, the 1960's were marked by steady head decline and a high rate of compaction. The decrease in ground-water pumpage in the early to middle 1970's was accompanied by a steady recovery of water levels and greatly reduced compaction. The resumption of large ground-water withdrawals during the 1976–77 drought was marked by a sharp decline in water levels and a short period of renewed compaction. Ireland and

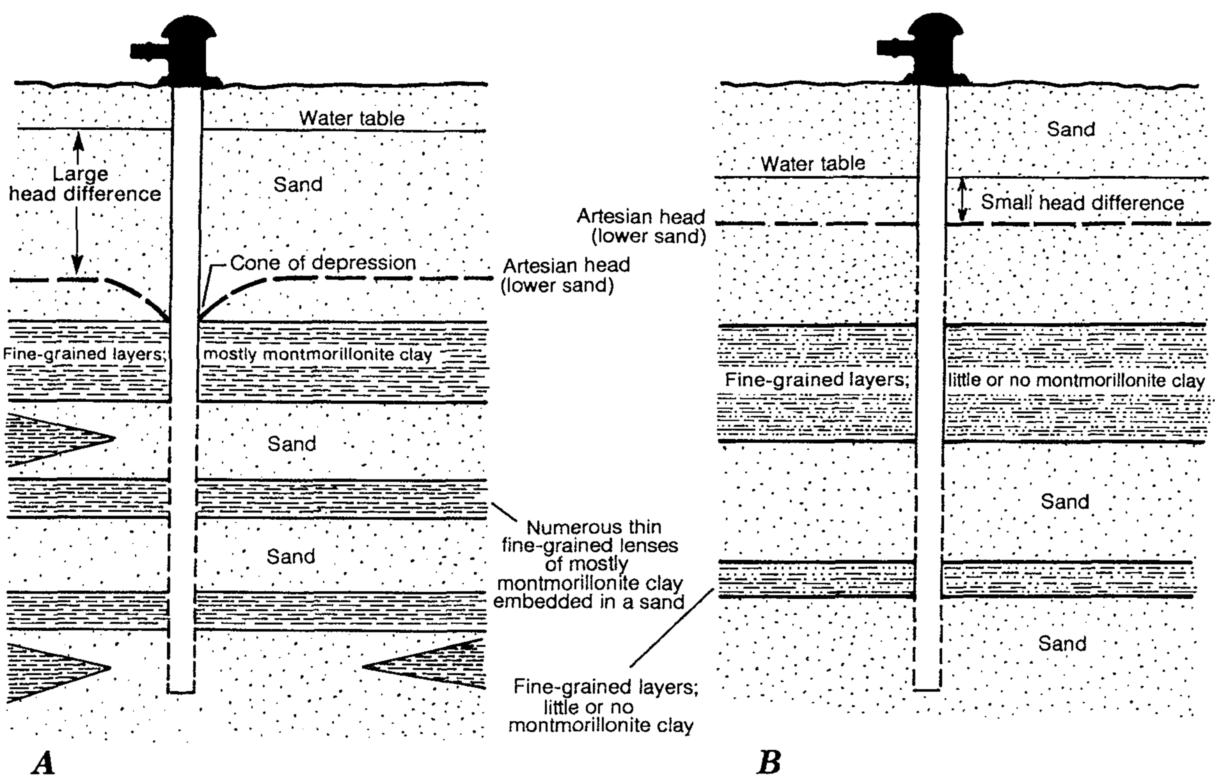


FIGURE 21.—Influence of hydrogeology and well construction on potential for land subsidence. Dashed lines denote perforated sections of wells. *A*, High potential for subsidence. *B*, Low potential for subsidence.

others (1984) reported that hydraulic heads generally declined 10 to 20 times as fast during the drought as during the period of long-term drawdown and compaction that ended in the late 1960's. In 1975, hydraulic heads were much higher than the lowest heads reached during the 1960's; consequently, when heavy pumpage resumed during the 1976–77 drought, very little compaction occurred. Pumpage was supplied by elastic storage (a small quantity) rather than by inelastic storage, so heads declined rapidly. Following the drought, recovery to predrought water levels was rapid and compaction virtually ceased.

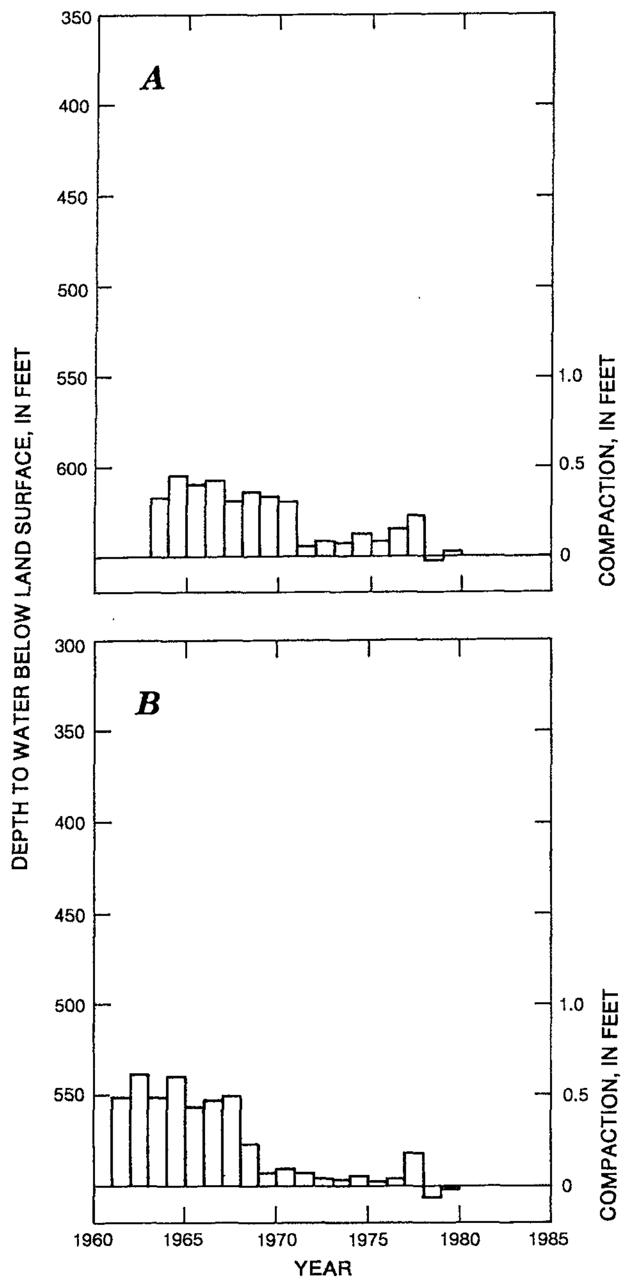


FIGURE 22.—Changes in hydraulic head and compaction at two wells in subsiding areas of San Joaquin Valley, 1960 to 1980 (modified from Ireland and others, 1984). *A*, Arvin-Maricopa area (well depth 1,480 ft). *B*, Los Banos-Kettleman City area (well depth 1,358 ft).

Areal Extent and Effects

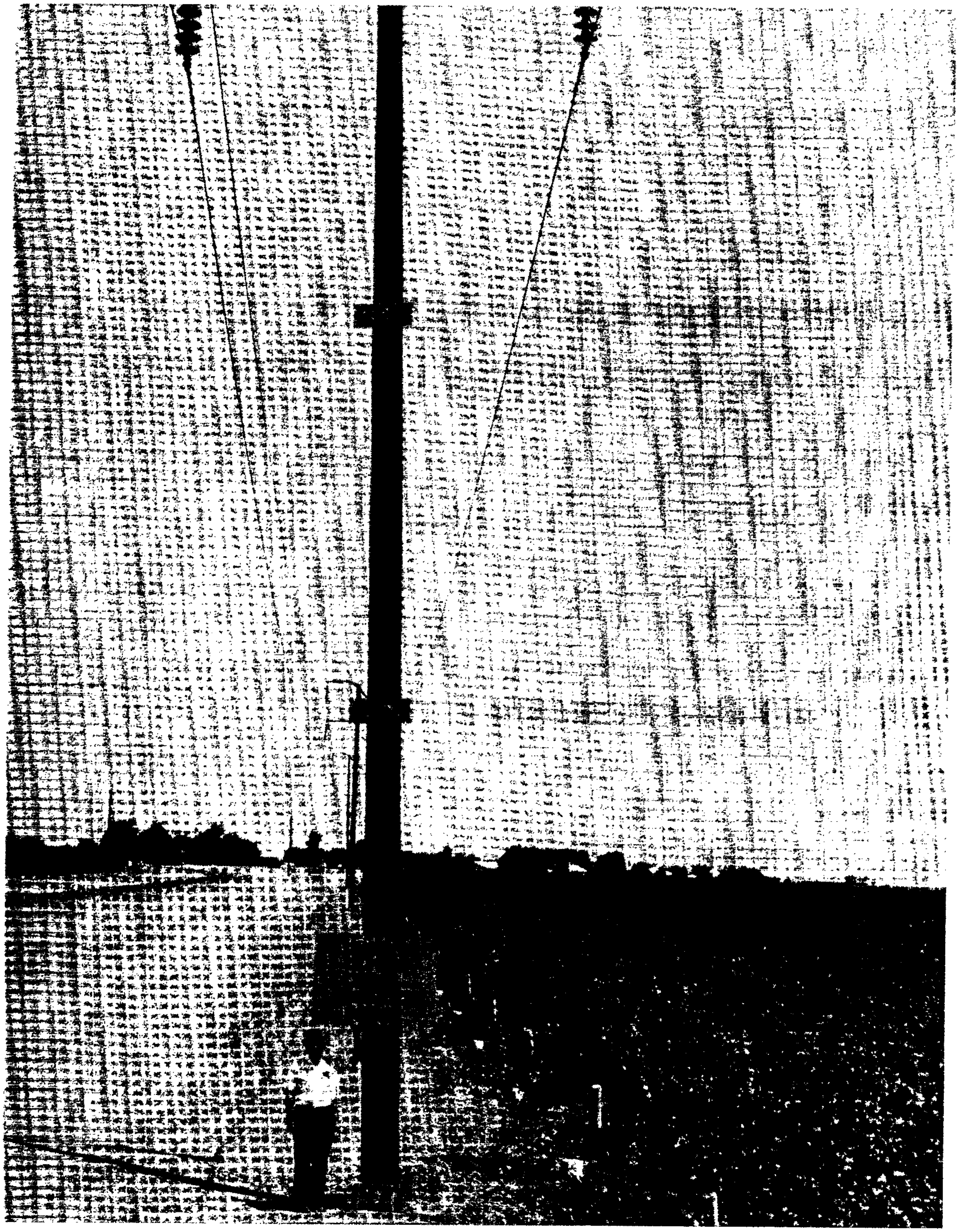
In the Central Valley, land has subsided largely in the San Joaquin Valley south of the Merced River. This subsidence was extensively documented by Poland and others (1975) and by Ireland and others (1984), and it is briefly summarized here. These two reports present detailed contour maps and profiles showing the areal extent and magnitude of subsidence and hydrographs relating water levels and compaction.

More than one-half of the San Joaquin Valley, or about 5,200 mi^2, has undergone land subsidence of more than 1 ft (fig. 19). Three major areas of subsidence within the valley are the Los Banos-Kettleman City area (western Fresno County), the Tulare-Wasco area (Tulare County), and the Arvin-Maricopa area (Kern County) (Poland and Lofgren, 1984). Of these, the Los Banos-Kettleman area underwent by far the largest volume of subsidence, amounting to two-thirds of the subsidence observed in the Central Valley up to 1980. This long trough-like area, extending for about 80 mi along the west margin of the valley, contains three depressions all characterized by more than 20 ft of subsidence at their centers. The maximum subsidence recorded in the United States (29.6 ft) is within one of these depressions in western Fresno County near the town of Mendota (fig. 23) (Ireland and others, 1984).

Subsidence began in the San Joaquin Valley in the 1920's and increased slowly until World War II. Very large increases in ground-water pumpage during the 1940's and 1950's caused the volume of subsidence to increase dramatically. Pumpage increased further through the mid-1960's at an average withdrawal rate of nearly 12 million acre-ft/yr and subsidence increased accordingly. As of 1970, the total volume of subsidence was 15.6 million acre-ft/yr (Poland and others, 1975).

▶

FIGURE 23.—Magnitude of subsidence at a site 10 mi southwest of Mendota in the San Joaquin Valley. Joseph F. Poland, principal subsidence researcher of the U.S. Geological Survey, alongside a power pole that shows approximate position of land surface in 1925, 1955, and 1977. Land surface was lowered 29.6 ft from 1925 to 1977.



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Ground-water pumpage declined sharply when surface water from the Sacramento Valley became available to the western San Joaquin Valley via the California Aqueduct in the late 1960's. Since 1970, there has been very little subsidence except during the 1976–77 drought, when pumpage from wells sharply increased and compaction briefly resumed (fig. 22). As of 1983, land subsidence in the San Joaquin Valley had either slowed considerably or stopped (Ireland, 1986). Locally in Fresno and Kings Counties, between 1977 and 1982, rebound of the land surface was significant (about 0.5 ft), indicating that subsidence during the 1976–77 drought was elastic. In the future, subsidence will resume only if renewed pumpage is sufficiently heavy to cause ground-water levels to drop below their previous lows.

In the Sacramento Valley, subsidence of more than 1 ft is limited to the Davis-Zamora area in the southern part of the valley northwest of Sacramento (fig. 19), where land subsidence of about 2 ft was reported by Lofgren and Ireland (1973). However, some additional leveling suggests that subsidence increased between 1973 and 1979 (Williamson and others, 1989).

Subsidence in the Central Valley has created engineering and economic problems, although many are not noticeable by casual observation because land subsided over such large areas at the same time. Subsidence of canals and irrigation and drainage systems has resulted in cracking and the loss of carrying capacity. In areas susceptible to hydrocompaction, it has been necessary to precompact sediments by prolonged wetting before construction of canals—a costly procedure. Failure of well casings due to compressional stress resulted in the loss of thousands of irrigation wells during the 1950's and 1960's. Frequent surveying to determine elevations of bench marks has been required for construction purposes and revision of topographic maps.

QUALITY OF GROUND WATER

Historically, ground-water quality of the Central Valley has been studied as three units: the Sacramento Valley, the San Joaquin Valley, and the Delta area (fig. 1). Olmsted and Davis (1961) described ground-water quality of the Sacramento Valley, Hull (1984) described ground-water quality of the Sacramento Valley exclusive of the southern part near the Delta, and Davis and others (1959) described ground-water quality of the San Joaquin Valley south of the Delta. Numerous authors of the U.S. Geological Survey described ground-water quality conditions in smaller parts of the valley, as indicated in the references.

Central Valley ground-water chemistry is influenced by water from streams that enter the valley from the surrounding mountains and provide most of the natural recharge (Davis and others, 1959; Hull, 1984). The quality of water in streams that enter the valley from the east is influenced by the granitic Sierra Nevada and is notably different from the quality of water in streams from the west, which is influenced by the marine sediments of the Coast Ranges. In general, the east side, the axial part, and the west side of the Central Valley are characterized by distinctive ground-water chemistry. The water chemistry is further influenced by an increase in reducing conditions and cation exchange processes as the water moves through the sediments.

Davis and others (1959) divided the San Joaquin Valley into three areas of ground-water-quality characteristics: the east side, the axial part, and the west side. In general, ground water on the east side is bicarbonate type and has low to moderate dissolved-solids concentrations, ground water of the axial part differs greatly in chemical types and generally contains higher concentrations of dissolved solids than does water on the east side, and ground water on the west side is typically a sulfate or bicarbonate type and contains higher concentrations of dissolved solids than does water on the east side (Davis and others, 1959).

Davis and others (1959) further divided ground water in the San Joaquin Valley into three vertical zones: unconfined, semiconfined, and confined. Confined waters generally have lower concentrations of dissolved solids and higher percent sodium. The confined waters also differ in chemical types from the unconfined waters owing to cation-exchange reactions, which occur on the clay particles (Davis and others, 1959).

Hull (1984), in a detailed study of the Sacramento Valley, delineated six hydrochemical facies: two on the east side, two in the center of the valley, and two on the west side. In general, ground water on the east side is low in dissolved solids and high in silica, reflecting the quality of recharge water from the granitic rock of the Sierra Nevada. Reducing conditions produce high concentrations of dissolved iron, manganese, and arsenic in the central part of the valley. Ground water on the west side is lower in silica and higher in dissolved-solids concentrations than ground water on the east side. Also, dissolved-solids concentrations tend to increase from north to south along the axis of the Sacramento Valley (fig. 24).

BASE OF FRESHWATER

The base of freshwater—less than 2,000 mg/L (milligrams per liter) of dissolved solids—in the Sacramento

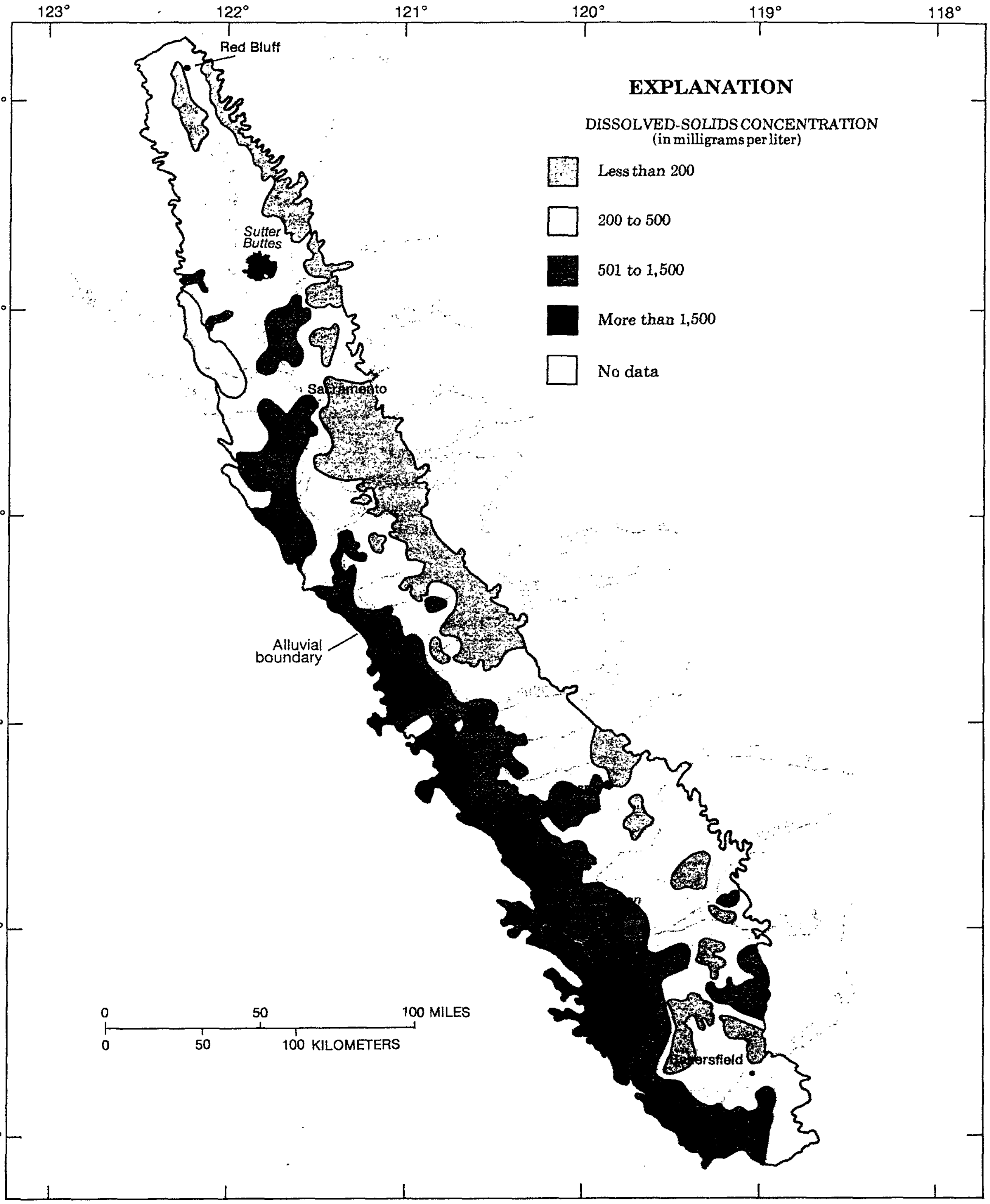

FIGURE 24.—Distribution of dissolved-solids concentrations in ground water of the Central Valley.

Valley was delineated by Berkstresser (1973). With the exception of several localized pods of shallow saline water, ground water in the continental and volcanic deposits of the Sacramento Valley is fresh. Several localized shallow saline zones were described by Berkstresser. Of these, four are now known to be underlain by freshwater. These shallow saline zones, underlain by freshwater, are located around the northern part of the Delta, along the Sacramento River, adjacent to the Sutter and Yolo bypasses, and around the base of Sutter Buttes. The zone around Sutter Buttes reflects the configuration of the underlying marine deposits (Berkstresser, 1973).

The base of freshwater as delineated by Page (1973b) for the San Joaquin Valley is more complex. In the San Joaquin Valley, the base of freshwater lies within the unconsolidated continental deposits of Pliocene to Holocene age, the more consolidated marine and sedimentary deposits of Tertiary age, and the igneous and metamorphic rocks of pre-Tertiary age. Unlike the Sacramento Valley, the base of freshwater in the San Joaquin Valley is underlain by a saline water body. The depths to the base of freshwater in the San Joaquin Valley range from less than 100 to more than 3,500 ft below land surface.

DISSOLVED SOLIDS

The areal distribution of dissolved-solids concentrations in ground water of the Central Valley is shown in figure 24. The map for the Sacramento Valley was prepared using a combination of data for dissolved solids measured by the residue-on-evaporation method (72 percent of the analyses) (Brown and others, 1970, p. 145) and data derived from specific conductance measurements (Fogelman, 1982a).

The map for the San Joaquin Valley was produced primarily from dissolved-solids measurements made using the residue-on-evaporation method. Where data were sparse, the map was modified by examining additional dissolved-solids data calculated as the sum of the dissolved constituents. Because 2,000 mg/L of dissolved solids is considered to be the maximum concentration in freshwater (Olmsted and Davis, 1961, p. 134), only those wells that yielded water with a dissolved-solids concentration of less than 2,000 mg/L were used to prepare the map. An exception to this was made along the southwest margin of the San Joaquin Valley, where shallow ground water has high dissolved-solids concentrations. The water samples were collected between 1974 and 1982 in the Sacramento Valley and between 1934 and 1985 in the San Joaquin Valley.

Because figure 24 is a two-dimensional representation of data compiled from existing wells with a wide variety of depths and screen lengths, the map cannot show vertical variations in water quality. It is therefore a generalization of the dissolved-solids concentrations that are likely to be found in a particular area, and it is most representative of the ground-water zones commonly used. About 11 percent of the wells in the Sacramento Valley data set yielded water with dissolved-solids concentrations that were higher or lower than the mapped interval. This proportion of concentrations not conforming to mapped intervals is probably similar for the San Joaquin Valley (Fogelman, 1982b).

The U.S. Environmental Protection Agency (1979) secondary drinking-water standards recommend a limit of 500 mg/L for dissolved solids. The California Domestic Water Quality Regulations allow a maximum of 1,000 mg/L if water of better quality is not available. However, because dissolved-solids concentrations only indicate the total amount of dissolved constituents in water, the usability of water that exceeds 500 mg/L needs to be evaluated according to the concentration of each chemical constituent.

Dissolved-solids concentrations are lower in the northern part and along the east side of the Central Valley. Dissolved solids are higher in the south-central part of the Sacramento Valley and in the western part of the San Joaquin Valley. This distribution reflects the low concentrations of dissolved solids in recharge water that originates in the Cascade Range and the Sierra Nevada, and the predominant regional ground-water flow pattern.

In the Sacramento Valley, dissolved-solids concentrations generally do not exceed 500 mg/L. Two large areas of shallow ground water in which concentrations of dissolved solids range from 500–1,500 mg/L are present in the southern part of the Sacramento Valley (fig. 24). One area is south of the Sutter Buttes in the Sutter basin, and the other is west of the Sacramento River extending from West Sacramento on the north to the confluence of the Sacramento and San Joaquin Rivers on the south (fig. 24).

In the San Joaquin Valley, dissolved-solids concentrations are lower on the east side and higher on the west side of the valley. In the center and on the east side of the valley, dissolved-solids concentrations generally do not exceed 500 mg/L; on the west side, most of the ground water contains concentrations of dissolved solids in excess of 500 mg/L. Concentrations of dissolved solids generally increase to the west, and concentrations in excess of 2,000 mg/L are not uncommon along the west margin of the valley.

HYDROCHEMICAL FACIES

Where a few ions dominate the dissolved-solids content of ground water, the term "hydrochemical facies" (Back, 1961) is used to describe the dominant ion patterns. The classification of ground water into hydrochemical facies or chemical water types is based on the relative concentration, in chemical equivalents, of cations and anions in the water. The cation and anion that represent at least 50 percent of the total ions are used to designate the chemical water type, such as magnesium bicarbonate. If no one cation or anion amounts to 50 percent, the water is designated by the two ions that make up the largest percentages, such as calcium magnesium bicarbonate.

The distribution of chemical water types in the Central Valley aquifer system is shown in figure 25. This map shows only the general distribution pattern of water types. Because the map does not show vertical variations, these variations are discussed herein, where appropriate. Areas where data are insufficient to define the water type were left blank.

SACRAMENTO VALLEY

Throughout the Sacramento Valley, with the exception of part of the Sutter basin, bicarbonate is the predominant anion in the ground water. Ground water in the northern and eastern parts of the Sacramento Valley has fairly homogeneous chemical character, with calcium and magnesium being the predominant cations. Two areas, one along Stony Creek and one along the Feather River, stand out as being exclusively calcium or magnesium bicarbonate, respectively, reflecting the recharge waters from the streams that drain into the valley at these locations (Fogelman, 1983).

South of the Sutter Buttes, water types are more complex and sodium is the predominant cation. Sodium bicarbonate type water is predominant along Salt Creek and downstream from the confluence of Salt Creek and the Sacramento River. The sodium ion in this area is probably derived from saline water in the Cretaceous formations that are drained by Salt Creek (Fogelman, 1983). Downgradient on the west side of the valley, and extending in a belt across the valley, is an area where the chemical type of ground water is predominantly magnesium sodium or sodium magnesium bicarbonate. The most notable exceptions to these water types are the areas adjacent to Cache and Putah Creeks and a small area around Dunnigan. The chemical water types in these areas are magnesium, calcium magnesium, or magnesium calcium bicarbonate. The water chemistry in the Dunnigan area is influenced largely by the Pliocene Tehama Formation, of which the Dunnigan Hills are largely composed (Fogelman, 1983). Recharge from Cache and Putah Creeks is the likely source of water in these areas. South of Putah Creek, sodium is again the predominant cation, although small pockets of calcium sodium and magnesium sodium ground water are also present.

Magnesium and calcium are the predominant cations in most of the southeastern part of the Sacramento Valley, and in particular, that area underlying the drainages of the American and Cosumnes Rivers. Smaller areas of sodium, sodium calcium, and sodium magnesium bicarbonate water types are also present in the southeastern Sacramento Valley.

The most notable exception to the predominance of bicarbonate as the major anion is the area in the southern part of Sutter basin just south of the Sutter Buttes. In this area, calcium, magnesium, and sodium, as well as chloride, bicarbonate, and sulfate may be found in any combination. Sutter Buttes may be the source of the high sodium and chloride concentrations (Fogelman, 1983), or the source may be a shallow layer of saline water surrounding the base of the Sutter Buttes (Berkstresser, 1973).

SAN JOAQUIN VALLEY

The distribution of water types or hydrochemical facies in the San Joaquin Valley is more complex than in the Sacramento Valley. The most important difference is the presence of chloride and sulfate as well as bicarbonate as the dominant anions. Generally, chloride predominates in the northwest, sulfate predominates in the southwest, and bicarbonate predominates in the east. The major exceptions to this are the Hanford-Visalia area, where chloride and bicarbonate predominate, and the extreme southeastern part of the valley, where bicarbonate, sulfate, and chloride are all present in varying concentrations.

On the basis of water types, three areas of the San Joaquin Valley can be delineated: the east side, predominantly bicarbonate; the axial trough, variable anion composition; and the west side, predominantly sulfate and chloride.

Water types of the east San Joaquin Valley are fairly uniform, most commonly resembling the chemical types of the local surface water that recharges the ground water (Dale and others, 1966; Croft and Gordon, 1968; Page and LeBlanc, 1969; Mitten and others, 1970; Sorenson, 1981). Calcium bicarbonate, calcium sodium bicarbonate, sodium calcium bicarbonate, and calcium magnesium bicarbonate are the predominant water types of ground water of the east side.

Because the axial trough has been the discharge area in the past for the San Joaquin Valley, ground water in this area is a combination of water from the east side and the west side (Croft and Gordon, 1968; Bertoldi, 1971). Local recharge from streams and surface water imported via canals that infiltrates from irrigated fields to the water table (Hotchkiss and Balding, 1971) also affects the ground-water chemistry of the axial trough.

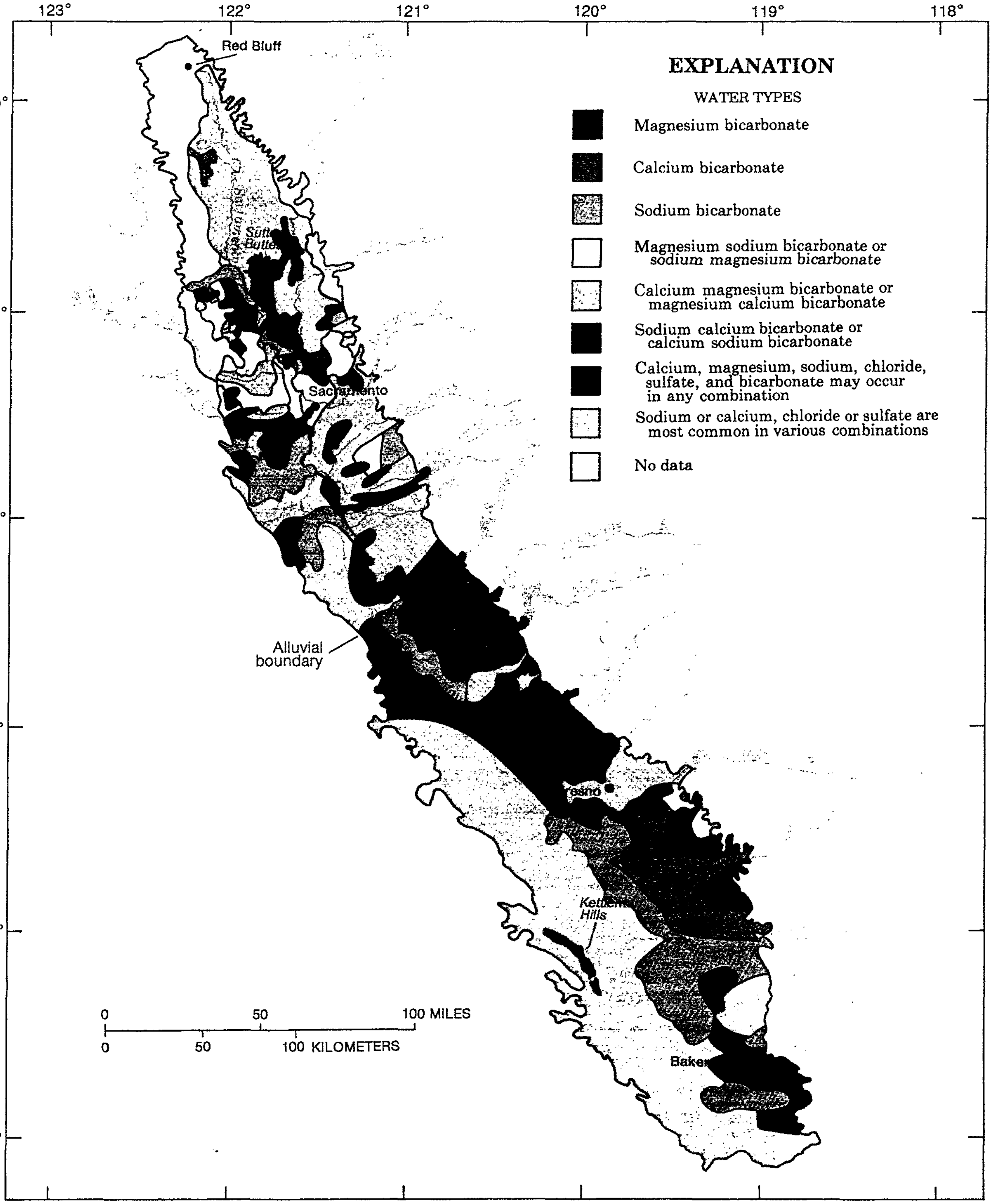

FIGURE 25.—Chemical types of ground water in the Central Valley. [Chemical types shown are approximated from maps and descriptions in the following reports: Davis and Poland, 1957; Wood and Davis, 1959; Wood and Dale, 1964; Dale and others, 1966; Croft and Gordon, 1968; Page and LeBlanc, 1969; Bertoldi, 1971; Hotchkiss and Balding, 1971; Page and Balding, 1973; Sorenson, 1981; Fogelman, 1983; Evenson, 1985; Johnson, 1985.]

Two depth zones are recognizable in the axial trough. In the lower zone, water types are generally sodium bicarbonate, sodium chloride, and calcium sodium bicarbonate. Ground water in the upper zone is more variable than in the lower zone.

Generally, sodium and calcium are the dominant cations of the axial trough ground water. In the northern part of the valley, chloride and bicarbonate are the dominant anions, and in the southern part of the valley, sulfate and bicarbonate are the dominant anions.

There is also a large amount of areal and vertical variability of water types on the west side of the San Joaquin Valley; here, in places, the Corcoran Clay Member of the Tulare Formation separates different types of ground water. Water types in the zone above the Corcoran Clay Member are less variable than those of the axial trough. Sodium is the predominant cation in this area with few exceptions. Sodium and sodium calcium predominate in the south, and sodium and calcium sodium predominate in the north. Sulfate is the predominant anion in the zone above the Corcoran Clay Member in the south (Davis and Poland, 1957; Wood and Davis, 1959; Hotchkiss and Balding, 1971), whereas chloride and bicarbonate predominate in the north. The presence of bicarbonate in the north is attributed to recharge from intermittent streams (Hotchkiss and Balding, 1971).

Chemical analyses for wells perforated below the Corcoran Clay Member north of the Fresno-Merced County line are limited, but the water type is probably similar to that above the clay. South of this area to the Tulare Lake bed, the water type below the Corcoran Clay Member is generally sodium sulfate (Bertoldi, 1971). The few wells that are perforated below the Corcoran Clay Member south of the Tulare Lake bed tap ground water that is generally sodium chloride (Dale and others, 1966).

PROBLEM COMPOUNDS

Local concentrations of boron, chloride, and nitrate in the Central Valley are high enough to be a problem either to crops or to humans. Other constituents, such as pesticides and trace metals, have been investigated only on a random basis and, with the exception of selenium in the western San Joaquin Valley, are not known to be a problem.

CHLORIDE

High chloride concentrations are generally not considered a health hazard. On the basis of taste preference, the U.S. Environmental Protection Agency (1979) recommends a limit of 250 mg/L for chloride in drinking water. High chloride concentrations can be toxic to plants, but salinity usually impairs growth before chloride alone reaches toxic levels. Water with chloride concentrations up to 700 mg/L can be used on most crops, depending on soils and irrigation practices, without impairing growth (National Academy of Sciences and National Academy of Engineering, 1973).

Chloride concentrations of Central Valley ground water generally are less than 250 mg/L; however, several areas are notable for having higher chloride concentrations.

Two bands of high chloride concentrations are located in the Sacramento Valley. One band is adjacent to Salt Creek near Williams; the other is adjacent to Petroleum and Salt Creeks near Arbuckle. In these areas, high chloride concentrations are attributed to the recharge from local streams (Bertoldi, 1976). A third area of high chloride concentrations is south of Sutter Buttes, in the southwestern part of the Sutter basin. This area coincides with a shallow saline water body previously described by Berkstresser (1973), which is probably the source of the high chloride concentrations.

The most notable locations of high chloride concentrations in the San Joaquin Valley are in the northwestern and north-central part of the valley along the course of the San Joaquin River and adjacent lowlands. Within this area, depth to the base of freshwater is shallower (500 ft or less) than elsewhere in the valley. Ground-water flow was upward prior to development and, currently, flow remains upward locally in this area (Williamson and others, 1989). Therefore, the most probable source of high chloride in the shallow ground water is upward flow of saline ground water. Sorenson (1981) mapped high chloride concentrations adjacent to and west of the San Joaquin River in San Joaquin and Contra Costa Counties. Others mapped high chloride concentrations all along the San Joaquin River (Page and LeBlanc, 1969; Mitten and others, 1970; Hotchkiss and Balding, 1971; Page and Balding, 1973).

BORON

Boron is a critical element in irrigation water supplies. In small quantities, boron is an essential micronutrient; however, boron becomes toxic to sensitive plants at concentrations as low as 0.75 mg/L and is toxic to most crops at concentrations exceeding 4.0 mg/L. Within this range, crops have been classified into three categories of boron tolerance: sensitive (less than 1 mg/L), semitolerant (1–2 mg/L), and tolerant (more than 2–4 mg/L) (National Academy of Sciences and National Academy of Engineering, 1973).

Boron is found in concentrations greater than 0.75 mg/L in several areas of the Central Valley. Small areas of high boron concentrations have been observed in the extreme northern and extreme southern parts of the valley. Fogelman (1983) delineated an area east of Red Bluff where ground water had concentrations of boron exceeding 0.75 mg/L. These high boron concentrations are attributed to the nearby Pliocene Tuscan Formation (Fogelman, 1983).

Wood and Dale (1964) reported concentrations of boron generally greater than 3 mg/L in the area southwest of Bakersfield and ranging from 1 to 4 mg/L in an area southeast of Bakersfield. Dale and others (1966) noted boron concentrations as high as 4.2 mg/L near Buttonwillow Ridge and Buena Vista Slough. The nearby marine sedimentary deposits were the probable source of the high boron concentrations of the west side, whereas the east side concentrations were probably derived from continental sedimentary deposits (Wood and Dale, 1964).

A large area of high boron concentrations in the southwestern part of the Sacramento Valley extends from Arbuckle on the north to Rio Vista on the south. There is one band of low boron water extending through the center of this area from Vacaville to West Sacramento. High boron concentrations in this area were attributed to marine deposits of the Upper Cretaceous Chico Formation and Lower Cretaceous rocks of the Coast Ranges, from which the recharge water is derived (Fogelman, 1983).

Another large area of high boron concentrations, in the northwestern part of the San Joaquin Valley, extends from the northernmost edge of the valley west of the San Joaquin River to the Kings-Fresno County line. Bertoldi (1971) reported high boron concentrations in the lower zone in the southern part of this area. Bertoldi also found high boron concentrations near the Diablo Range, indicating that these marine sediments of the range are the likely source of the boron. Sorenson (1981) also attributed high boron concentrations in the northern part of the valley to the marine sediments of the Coast Ranges.

NITRATE

Nitrate toxicity usually does not affect adults, but it can cause a blood disorder known as methemoglobinemia, which is sometimes fatal in infants and young children. The recommended maximum concentration in drinking water for nitrate (as nitrogen) is 10 mg/L (National Academy of Sciences and National Academy of Engineering, 1973).

Nitrate in irrigation water is usually considered an asset because of its value as a fertilizer. However, some crops such as sugar beets, apricots, grapes, citrus, and avocados are sensitive and may be adversely affected by high nitrate concentrations. Problems can result from concentrations as low as 5 mg/L, and severe problems result from concentrations above 30 mg/L (Ayers, 1977).

Concentrations of nitrate as nitrogen exceeding 30 mg/L are very rare and extremely localized in the Central Valley. However, there are several areas where concentrations exceed 10 mg/L.

Several potential problem areas were delineated in the Sacramento Valley with respect to nitrates in drinking water (Fogelman, 1983). Hull (1984) estimated the maximum concentration of nitrate under natural conditions of the Sacramento Valley to be 3 mg/L and considered that areas having 5.5 mg/L or more are those in which nitrate concentrations may be increasing. Forty wells in the Chico-Corning area contained water in which nitrate-nitrogen concentrations exceeded 5.5 mg/L, and 25 percent of these wells contained water with concentrations exceeding 10 mg/L. In the Gridley-Marysville area, 21 wells contained water in which concentrations of nitrate-nitrogen exceeded 5.5 mg/L, and 33 percent of these contained water with concentrations exceeding 10 mg/L. In both areas, the wells containing high nitrate concentrations are shallow, and surface contamination from leaching of applied nitrate fertilizers, urban waste-treatment facilities, or septic systems was suggested as the probable cause (Fogelman, 1983).

Sorenson (1981) reported nitrate concentrations greater than 5 mg/L over a large part of southern San Joaquin County between Lodi and Stockton. These high concentrations were attributed to agricultural practices.

In several other small areas of the San Joaquin Valley, ground water contains concentrations of nitrate exceeding 10 mg/L. Such an area south of Bakersfield was identified by Wood and Dale (1964) and 2 years later another such area slightly north of Bakersfield was identified by Dale and others (1966). High concentrations also have been reported around the Fresno metropolitan area. In this area, nitrate concentrations decrease with depth (Page and LeBlanc, 1969), indicating surface contamination. Sporadic high concentrations of nitrate were also found near the foothills of the Sierra Nevada in the Hanford-Visalia area (Croft and Gordon, 1968). Other occurrences of nitrate-nitrogen exceeding 10 mg/L are extremely localized and usually are attributed to localized pollution sources such as septic tanks, dairies, or feed lots (Sorenson, 1981; Bertoldi, 1971).

EFFECTS OF HUMAN ACTIVITIES

Temporal changes in dissolved-solids and nitrate concentrations in the Sacramento Valley were studied by Hull (1984). Dissolved-solids concentrations were used as an indicator of changes in the overall water quality, and nitrate concentrations were used as an indicator of human sources such as applied fertilizers or human waste. Significant increases in concentrations of both dissolved solids and nitrates were observed, indicating that ground-water quality is degrading as a result of increasing application of agricultural chemicals and growth of urban population.

The concentrations of dissolved solids increased significantly since the 1950's throughout the Sacramento Valley except for an area south of Sutter Buttes between the Sacramento and Feather Rivers (Hull, 1984). However, increases in nitrate concentrations were found only on the west side and in the southeastern part of the valley (Hull, 1984). Hull (U.S. Geological Survey, oral commun., 1984) indicated that the rate of nitrate build-up has been increasing since 1912. He found that in 1912 to 1913, 2.2 percent of the wells had nitrate concentrations greater than 5.5 mg/L; between 1960 and 1969, 4.9 percent had concentrations exceeding 5.5 mg/L, and from 1974 to 1978, 10.5 percent had concentrations exceeding 5.5 mg/L.

Studies to determine human impact on ground-water quality in the San Joaquin Valley were not done, largely because different time periods of sample collection and the use of different analytical techniques make the comparability of the existing data questionable. Because agricultural practices in the San Joaquin Valley are similar to those in the Sacramento Valley, it is likely that ground-water quality in the San Joaquin Valley is also degrading as a result of human activities. However, differences in geology, soils, and irrigation techniques could all affect the impact of human activities. Areas of possible contamination of ground water due to human activities in the San Joaquin Valley were mapped by Templin (1984, pl. 8). Sources listed were industrial, municipal and domestic solid-waste disposal sites, and agricultural chemical build-up. This map suggests that human-induced contamination exists throughout much of the valley.

The use of pesticides is another possible impact on ground water that has not been studied in detail. Pesticides have been used intensively in the Central Valley for many years and because dissolved-solids and nitrate concentrations are increasing, it is likely that pesticide concentrations in ground water also are increasing.

The presence of dibromochloropropane (DBCP) in ground water in the San Joaquin Valley was mapped by Templin (1984, pl. 7D). The presence of this pesticide at levels above 0.0005 mg/L near Bakersfield, Fresno, Modesto, and north of Merced and Stockton coincides with land-use patterns. More specifically, these areas are occupied by orchards and vineyards, where DBCP is commonly used. The presence of DBCP in the San Joaquin Valley suggests that other pesticides have probably built up in ground water of the Central Valley.

Selenium, which is toxic to humans and animals at very low concentrations, occurs naturally in the soils and ground water on the west side of the San Joaquin Valley (Deverel and others, 1984). Ecological and health effects of selenium and other trace elements in agricultural drainage water on the west side of the San Joaquin Valley have become subjects of extensive study since high incidences of mortality and birth defects were observed in waterfowl nesting in the area where drainage water is discharged (U.S. Bureau of Reclamation, 1984). In a preliminary study (Deverel and others, 1984), the areal distribution of selenium and other inorganic constituents was examined along the west side of the valley west of Fresno. Selenium concentrations (median concentrations of 10–11 mg/L) were highest in the central and southern parts (south of Los Banos and south of Mendota) of the area studied. Extensive studies by U.S. Department of Interior agencies (Bureau of Reclamation, Fish and Wildlife Service, and the Geological Survey) and also many studies by universities, State water resources agencies, and concerned local agencies are still in progress (1989).

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